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# ANNUAL REPORT OF RESEARCH AND TECHNOLOGIC WORK ON COAL, FISCAL YEAR 1942

BY

A. C. FIELDNER AND W. E. RICE

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UNITED STATES DEPARTMENT OF THE INTERIOR - BUREAU OF MINES

# ANNUAL REPORT OF RESEARCH AND TECHNOLOGIC WORK ON COAL, FISCAL YEAR 1942[1]

By Arno C. Fieldner[2] and W. E. Rice[3]

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1/ The Bureau of Mines will welcome reprinting of this paper, provided the following acknowledgment is used: "Reprinted from Bureau of Mines Information Circular 7241."

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## INTRODUCTION

The annual reports of the research and technologic investigations conducted by the Bureau of Mines on the occurrence, properties, mining, preparation, and uses of coal, of which the present report is the seventh,[4] are intended to be brief summaries of progress. They are guides to the current work and publications of the Bureau but do not replace the more complete reports published by individuals and groups of workers on specific problems. The annual reports present the results of tests, often in advance of publication in other forms, but original contributions in research are reserved for initial publication by their authors.

A survey of the accomplishments of the Bureau in research and technologic work on coal during the 5 year period 1935-40 has been made available in the form of a bibliography.[5] This supplements a similar bibligraphy on this subject that covers the first 25 years of the Bureau, 1910-35.[6]

---

4/ Fieldner, A. C., Résumé of Research and Technologic Work Relating to Coal Conducted by the Technologic Branch During 1936: Bureau of Mines Inf. Circ. 6935, 1937, 14 pp. Annual Report of Research and Technologic Work on Coal, Fiscal Year 1937: Bureau of Mines Inf. Circ. 6992, 1938, 44 pp. Annual Report of Research and Technologic Work on Coal, Fiscal Year 1938: Bureau of Mines Inf. Circ. 7052, 1939, 44 pp.
Fieldner, A. C., and Brewer, R. E., Annual Report of Research and Technologic Work on Coal, Fiscal Year 1939: Bureau of Mines Inf. Circ., 7105, 1940, 59 pp.
Fieldner, A. C., and Rice, W. E., Annual Report of Research and Technologic Work on Coal, Fiscal Year 1940: Bureau of Mines Inf. Circ. 7143, 1940, 50 pp.
Fieldner, A. C., and Schmidt, L. D., Annual Report of Research and Technologic Work on Coal, Fiscal Year 1941: Bureau of Mines Inf. Circ. 7190, 1941, 60 pp.

5/ Fieldner, A. C., Bibliography of Bureau of Mines Investigation of Coal and Its Products, 1935 to 1940: Bureau of Mines Tech. Paper 639, 1942, 43 pp.

6/ Fieldner, A. C., Emery, Alden H., and von Bernewitz, M. W., Bibliography of United States Bureau of Mines Investigations on Coal and Its Products, 1910-35: Bureau of Mines Tech. Paper 576, 1937, 145 pp.



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A general review of reserach and progress in the production and use of coal and discussion of desirable plans for furure research was compiled for the use of the National Resources Planning Board.7/ This comprises chapters prepared by members of the staff of the Bureau of Mines on mining, preparation, combustion, carbonization, gasification, and liquefaction of coal. Each chapter reviews the relation of progress to research in the field covered and concludes with a statement of projects for future research insofar as these can be forseen in the light of present developments. The coal reserves of this country are so large that efficient production and utilization of coal will be a perennial problem, and it is a conservation measure to engage in long-term fundamental research on a scale commensurate with the importance of coal in industrial activities.

## ACKNOWLEDGMENTS

This report includes work done under the supervision of the following members of the staff of the Technologic Branch of the Bureau of Mines:

### Coal Division

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H. M. Cooper, supervising chemist, Coal Analysis Section.
J. D. Davis, supervising chemist, Coal Carbonization Section.
H. P. Greenwald, superintendent, Central Experiment Station, and supervising engineer, Experimental Coal Mine Section.
V. F. Parry, supervising engineer, Subbituminous Coal and Lignite Section.
W. T. Reid, acting supervising engineer, Fuels Section.
W. A. Selvig, supervising chemist, Coal Constitution and Miscellaneous Analysis Section.
N. H. Snyder, supervising engineer, Fuel Inspection Section.
H. H. Storch, supervising chemist, Coal Hydrogenation and Physical Chemistry section.

### Explosives Division

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G. W. Jones, supervising chemist, Gas Explosions Section.
M. A. Elliott, supervising engineer, Explosives and Diesel Engine Research Section.
J. E. Tiffany, supervising engineer, Explosives Testing Section.

7/ Fieldner, A. C., and Rice, W. E., Research and Progress in the Production and Use of Coal: Nat. Resources Planning Board Tech. Paper 4, 1941, 49 pp.



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Nonmetals Division

O. C. Ralston, chief engineer.
W. H. Coghill, supervising engineer, Southern Experiment Station.
H. F. Yancey, supervising engineer, Northwest Experiment Station.

Acknowledgment is made also of the cooperation of the following institutions and organizations:

American Society of Heating and Ventilating Engineers.
American Society of Mechanical Engineers.
American Society for Testing Materials.
Colorado School of Mines.
Combustion Engineering Co.
Illinois Geological Survey.
Office of the Bituminous Coal Consumers' Counsel.
Office of the Solid Fuels Coordinator for War.
Oklahoma Geological Survey.
University of North Dakota.
University of Washington.

## PROPERTIES AND COMPOSITION OF AMERICAN COALS

### Inspection, Sampling, and Analysis

Four coal-sampling trucks were operated continuously to obtain analyses for use in awarding contracts for the supplying of coal to the Government. This work assumed special significance during 1942 as a result of increasing demand of the armed forces for fuel. These trucks were taken to 439 mines in 14 States, where 1,470 samples of bituminous coal were prepared; these comprised 3 samples from Arkansas, 328 from Colorado, 40 from Illinois, 52 from Indiana, 158 from Kentucky, 29 from Montana, 9 from Ohio, 18 from Oklahoma, 49 from Pennsylvania, 173 from Tennessee, 177 from Utah, 168 from Virginia, 178 from West Virginia, and 95 from Wyoming. In addition, 186 samples were prepared at 26 breakers in the Pennsylvania anthracite region, and 41 samples were prepared at 11 dredging operations in rivers and creeks that drain the anthracite region. During the past 20 years, the average recovery of anthracite by dredging has been three quarters of a million tons annually, or a little more than 1 percent of the total production of anthracite.



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The quality of the coal recovered by dredging varies greatly, depending on conditions that affect the flow of the streams.8/

In connection with the inspection of purchased coal the coal-analysis laboratory reported the analyses of 9,391 samples, representing approximately 4 million tons of coal. In addition 1,082 samples were analyzed to correlate analyses with the research of the Bureau on the utilization of coal by combustion, carbonization, gasification, and hydrogenation.

Federal coal-mine inspectors submitted 4,752 samples collected in inspections conducted to increase safety and establish healthful conditions in coal mines. These samples consist of coal and rock dust in varying proportions, taken from roads, ribs, and roofs of mines. Sizes of particles were determined, in addition to the usual analyses of these samples.

Analyses of Illinois Coals

A new volume was added to the series of publications that describe the coals of individual producing States. In the past 12 years Illinois has produced 10.81 to 12.02 percent of the bituminous coal mined in the United States, and in the 7 years from 1933 to 1939, its output was exceeded only by that of West Virginia and of Pennsylvania. A compilation9/ of analyses of Illinois coals from the Bureau of Mines files is supplemented by chapters on the geology of the coal field, methods of mining and preparation, and statistics of production, distribution, and uses. Descriptions of samples collected in the mines include detailed information on thickness of beds, nature of floor and roof, and partings in the beds.

Analyses of West Virginia Coals

A new volume of Analyses of West Virginia Coals10/ comprises all analyses previously published in Bureau of Mines Technical Paper 405 (1928) and later analyses made before January 1, 1940. The information on geology, mining, distribution, and uses has been revised.

---

8/ Corgan, Joseph A., Dredging Pennsylvania Anthracite: Bureau of Mines Inf. Circ. 7213, 1942, 25 pp.

9/ Fieldner, A. C., Cady, Gilbert H., Toenges, Albert L., Maize, Earl R., Fraser, Thomas, Anderson, R. L., McBride, J. W., Snyder, N. H., Cooper, H. M., Abernethy, R. F., Tarpley, E. C., and Swingle, R. J., Analyses of Illinois Coals: Bureau of Mines Tech. Paper 641, 1942, 245 pp.

10/ Fieldner, A. C., Price, Paul N., Heck, E. T., Toenges, A. L., Anderson R. L., Snyder, N. H., Cooper, H. M., Abernethy, R. F., Tarpley, E. C., and Swingle, R. J., Analyses of West Virginia Coals: Bureau of Mines Tech. Paper 626, 1943, 341 pp.



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Typical Analyses of Coals of the United States

The Bureau files contain analyses of more than 300,000 samples of coal. As a result of a thorough survey of these analyses, a brief summary of the commercial coal resources of the country has been made available.11/ Specimen analyses are given exemplifying the analysis of coal mined in each coal-producing county, or, where it is feasible, coal from each bed in each county; moreover, ranges of analyses, within which the composition of most of the coal represented will fall, are given where there are enough analyses to permit satisfactory determination of the ranges.

The same typical anlyses, with those for some screen-sized coals, are being published by the United States Office of the Bituminous Coal Consumers' Counsel in a series of data books which, in addition, contain descriptive tables of rail and river shipping mines and maps showing their location. These data books describe the producing districts as defined in the Bituminous Coal Act of 1937 12/ and they have proved of great value to retail dealers and the larger industrial consumers.

Heating Value of Coal

There is a general belief in the coal trade that although the moisture- and ash-free heating value of coal varies in coals of different rank, it is substantially constant for coal from the same bed, or more especially, coal from the same mine. If so, calculation of this value from the usual coal analysis and calorimetric value would reveal that a coal did not come from a given area or bed, and for restricted areas it would reveal the probable origin. To determin

11/ Fieldner, A. C., Rice, W. E., and Moran, H. E., Typical Analyses of Coals of the United States: Bureau of Mines Tech. Paper 446, 1942, 45 pp.

12/ Consumers' Counsel Division, Office of the Solicitor, U. S. Department of the Interior, Typical Analyses, Bituminous Coals Produced in District 7 and 8: Data Book, vol. 1, 1941, 28 pp. (in cooperation with the Bureau of Mines).
Office of the Bituminous Coal Consumers' Counsel, Typical Analyses, Bituminous Coals Produced in District 1: Data Book, vol. 2, 1941, 18 pp (in cooperation with the Bureau of Mines). Typical Analyses, Bituminous Coals Produced in Districts 2, 3, 4, 5, and 6: Data Book, vol. 3, 1941, 29 pp. (in cooperation with the Bureau of Mines). Typical Analyses, Bituminous Coals Produced in District 13: Data Book, vol. 4, 1942, 11 p (in cooperation with the Bureau of Mines).
U. S. Office of Bituminous Coal Consumers' Counsel, Typical Analyses, Bituminous Coal, Districts 10 and 11: Data Book, vol. 5, 1942, 48 pp. (in cooperation with the Bureau of Mines).



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the possible limitations or the accuracy of this idea, a large number of analyses of coal from 13 mines that produce coal ranging in rank from anthracite to lignite was carefully studied.13/ This study indicates deviations from the average of not more than 100 B.t.u. per pound for coals of low- and medium-volatile bituminous rank but increasing to 800 B.t.u. per pound with change of rank in either direction, that is, toward anthracite or toward lignite.

Moisture in Coal

Accurate determination of the moisture content of coal is particularly important in acceptance tests of steam-generating equipment where there is a contract that includes a high penalty or bonus. In cooperation with the Combustion Engineering Co. a series of comparisons was made of samples collected in large ashcans; samples collected and air-dried in large cloth bags in the boiler room and grab samples taken from these cans and bags before the gross samples were crushed and reduced.14/ If the moisture content of the bag samples is considered to be correct for the coal the average moisture content of the ashcan samples is 0.60 percent low, and that of the grab samples is 0.28 percent low.

Determination of Ash of Coals High in Calcite and Pyrite

Cooperative work between the Bureau of Mines and the Illinois Geological Survey on methods of determining ash in coals high in calcite and pyrite established the fact that the determination is best started in a cold furnace, which is then heated to 750° C. in 1-1/2 hours or longer. By this procedure much of the sulfur of the pyrite is oxidized and expelled before the calcite is decomposed, less is retained as calcium sulfate in the ash, and a lower percentage of ash is indicated.15/

Standard Methods and Specifications

The Bureau of Mines cooperates with the American Society for Testing Materials in the formulation of methods of sampling, analyzing, and testing coal and coke and in the preparation of specifications for the classification of coals on the basis of physical and chemical characteristics for use in homes and industries. Changes were recommended to improve the procedure for determining ash in coals high in calcite and pyrite; a method of test for index

13/ Barkley, J. F., and Burdick, L. R., The Various B.t.u. Values of a Coal: Bureau of Mines Inf. Circ. 7193, 1941, 26 pp.

14/ Barkley, J. F., Determining Moisture Content of Coal: Combustion, vol. 13, 1941, pp. 50-51.

15/ Rees, O. W., and Selvig, W. A., Determination of Ash in Coals Unusually High in Calcite and Pyrite: Ind. Eng. Chem., anal. ed., vol. 14, 1942, pp. 209-212.



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of dustiness of coal and coke was recommended for adoption as a tentative standard; it was recommended that the present tentative standard definition of coke and the standard specification for foundry coke be withdrawn.16/

## Properties of Fuels

A revised chapter on the properties of solid, liquid, and gaseous fuels was prepared by the staff of the Bureau for a new edition of the Mechanical Engineers' Handbook.17/ Information is included on a number of fuels that have come into use since publication of the earlier edition and on properties that previously were not considered in the selection and use of fuels.

## Chemical Method for Estimation of Fusain

A report18/ was published on comparative results in the determination of fusain in coal by chemical oxidation19/ and petrographic methods. The coals examined included splint coal, bright coal, anthraxylon, cannel coal, and fusain separated from column samples of various beds.

Table 1 shows the fusain content of the coal samples as determined by the chemical oxidation method and by microscopic examination. The samples represent a wide range in type and rank of coal.

In general, reasonably good agreement was obtained by the chemical oxidation and petrographic methods. Duplicate determinations by the chemical oxidation method showed good agreement. This method has the advantage of simple, well-known technique, whereas the petrographic method requires familiarity with the petrography of coal.

---

16/ Fieldner, A. C., and Selvig, W. A., Report of Committee D-5 on Coal and Coke: Proc. 44th Ann. Meeting, Am. Soc. Testing Materials, vol. 41, 1942, pp. 370-374.

17/ Fieldner, A. C., and associates in the Bureau of Mines, Fuels: Mechanical Engineers' Handbook (ed. by Lionel S. Marks). 4th ed., McGraw-Hill Book Co., Inc., New York, 1941, pp. 782-825.

18/ Selvig, W. A., Ode, W. H., and Sprunk, G. C., A Comparison of the Determination of Fusain in Coal by Chemical Oxidation and Petrographic Methods: Fuel, vol. 21, 1942, pp. 33-36.

19/ Fuchs, Walter, Gauger, A. W., Hsiao, C. C., and Wright, C. C., The Chemistry of the Petrographic Constituents of Bituminous Coal. Part I. Studies on Fusain: Pennsylvania State College Mineral Industries Experiment Station Bull. 23, 1938, pp. 24-27.



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TABLE 1. - Fusain content of coals of various rank and type as determined chemically and petrographically

| Sample designation | Bed | Mine | County | State | Proximate analysis, moisture-free basis | | | Fusain, percent | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | Volatile matter | Fixed carbon | Ash | Moisture- and ash-Free Basis, Chemical oxidation method, Test 1 | Test 2 | Petrographic method |
| Fusain | Pittsburgh | Bruceton | Allegheny | Pa. | 13.9 | 77.7 | 8.4 | 86 | 86 | 90 (approximate) |
| Do. | Lower Kittanning | Indian Creek No. 1 | Fayette | Do. | 9.1 | 85.1 | 5.8 | 84 | 84 | 90 (approximate) |
| Do. | Beckley | Winding Gulf No. 1 | Raleigh | W. Va. | 10.1 | 86.6 | 3.3 | 89 | 90 | 90 (approximate) |
| Splint coal (high-volatile A bituminous) | Coalburg | Silush | Boone | Do. | 42.1 | 55.6 | 2.3 | 1.4 | 1.9 | 2 |
| Do. | High Splint | Closplint | Harlan | Ky. | 28.9 | 61.7 | 9.4 | .6 | .8 | 2 |
| Splint coal (low-volatile bituminous) | Beckley | Winding Gulf No. 1 | Raleigh | W. Va. | 16.9 | 80.9 | 2.2 | 2.1 | 2.3 | 4 |
| Bright coal (subbituminous B) | Monarch | Monarch No. 45 | Sheridan | Wyo. | 42.8 | 52.8 | 4.4 | .3 | .3 | 1 |
| Bright coal (low-volatile bituminous) | Beckley | Winding Gulf No. 1 | Raleigh | W. Va. | 17.7 | 78.6 | 3.7 | 6.9 | 7.5 | 7 |
| Anthraxylon (low-volatile bituminous) | Do. | Do. | Do. | Do. | 20.2 | 78.8 | 1.0 | .4 | .3 | Less than 0.5 |
| Cannel coal (high-volatile A bituminous) | - | American Fire Clay & Products Co. | Mahoning | Ohio | 40.6 | 43.2 | 16.2 | 1.2[a] | 1.2[a] | Less than 1. |

a Moisture- and mineral-matter-free basis.



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## Relation of Petrographic Composition to Chemical and Physical Properties of Coal

A summary of Bureau of Mines data on the relation between petrographic composition and the chemical, hydrogenating, and carbonizing properties of coal was presented at the geological program in celebration of the Fiftieth Anniversary of the University of Chicago, held under the joint sponsorship of the Geological Society of America, the American Association for Advancement of Science, and the University of Chicago. This paper[20] emphasizes the importance of recognizing type as well as rank when studying the properties of coal.

### Relation of Petrography to Carbonizing Properties of Coal

Data now available show that certain carbonizing properties of medium-volatile coals are not predictable from chemical analyses and that petrographic composition may modify these properties more than has been recognized generally.[21] Table 2 shows the petrographic composition and coking tests of four medium-volatile Appalachian coals.

TABLE 2. - Carbonizing characteristics and petrographic composition of four Appalachian coals

| Coal | Dry, mineral-matter free fixed carbon percent | Types, percent | | | | 900° coke | | Expansion in sole-heated oven, percent |
|---|---|---|---|---|---|---|---|---|
| | | Bright | Semi-splint | Splint | Cannel | 1-1/2-inch (shatter index) | 1-inch (tumbler index) | |
| Lower Freeport | 73.4 | 93 | 4<br>5 | 2 | 0 | 88.9 | 69.8 | +19.0 |
| Lower Banner | 76.9 | 36 | 53 | 0 | 11 | 82.6 | 65.4 | -6.2 |
| Bakerstown | 77.1 | 91 | 3 | 6 | 0 | 88.0 | 72.3 | +9.8 |
| Sewell | 77.5 | 81 | 15 | 4 | 0 | 85.7 | 68.9 | +16.0 |

20/ Sprunk, G. C., Influence of Physical Constitution of Coal Upon Its Chemical, Hydrogenation, and Carbonization Properties: Jour. Geology, vol. 1, no. 4, May-June, 1942, pp. 411-436.

21/ Reynolds, D. A., and Davis, J. D., Coal Carbonization: Carbonization Properties of Medium-Volatile Coals of Different Types: Paper presented at meeting of Am. Chem. Soc., Atlantic City, September 8-12, 1941.



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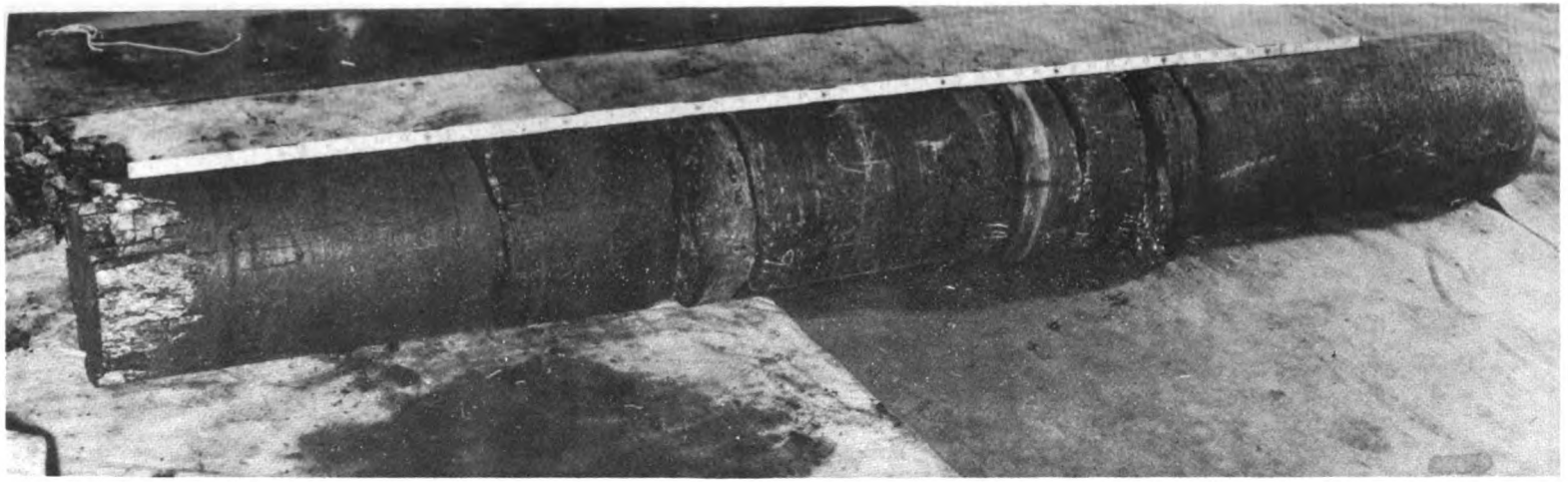

Figure 1.—Core from bed A, drill hole 1-35, Sanpete County, Utah.

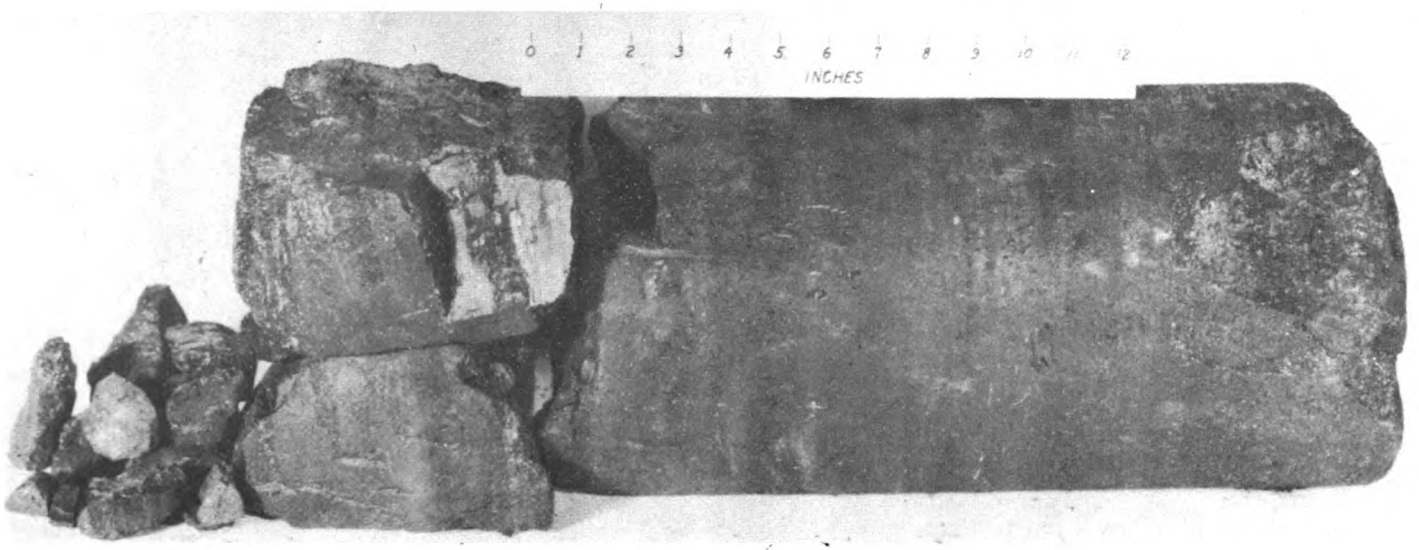


Figure 2.—Core from bed B, drill hole 1-35 Sanpete County, Utah.

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The Lower Freeport, Bakerstown, and Sewell coals are predominantly bright, but the Lower Banner bed contains considerable semisplint and cannel coal. The Lower Banner differs from the other three in that it forms the weakest coke, as determined by both tumbler and shatter tests. The Lower Banner also differs in that it contracts during carbonization, whereas the others expand. The expansion properties of coals are given important consideration in selecting coals for coking, because it is often necessary to dilute highly expanding coals with nonexpanding coals to prevent injury to coke ovens.

In the survey of gas- and coke-making properties of American coals, most of the cokes made from high-volatile coals containing large amounts of splint did not differ appreciably from the bright coals, as far as was shown by tumbler and shatter tests. However, it is believed that cokes from the medium- and low-volatile-group coals will be more sensitive to change in type of coal than those of the high-volatile group. Unfortunately most of the coals that have been tested in the low- and medium-volatile groups are bright coals.

Coking Properties of Utah Coal. - In connection with the program for finding new supplies of coking coals in the Western States, drill cores from coal beds in Sanpete County, Utah, were examined and compared with a column of coal from the Lower Sunnyside bed, Horse Canyon mine, Emery County, Utah. Complete cores were received from bed A and bed B, and part of a core was received from bed E. The cores from beds C, D, and F were crushed badly and were unsuitable for microscopic examination. Figure 1 shows the drill core from bed A, and figure 2 shows that from bed B. The cores were used for carbonization tests and microscopic examination.

The microstructure indicates little difference in the carbonizing properties of beds A, B, and E, because the average proportion of components is about the same for each bed. The difference between the carbonizing characteristics of these beds and those of the Lower Sunnyside bed from the Horse Canyon mine may be attributed to difference in both microstructure and rank of coal. The Lower Sunnyside is a higher-rank coal, as measured by oxygen and total carbon. On the other hand, beds A, B, and E all contain more volatile matter, probably owing to the high resin content of these coals. It is believed that the resins increase the agglutinating value over that of a normal coal and contribute to the fingery structure of coke that was obtained.

Analyses of the coals and results of coking tests of the samples from a single hole are given in table 3. These data were confirmed by examination and testing of cores from other holes.

Calculation of the ash in volatile matter-free coal shows that the lower beds contain too much ash for making coke. The coals, containing much resin and little fusain and opaque matter, should hydrogenate easily and completely.



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TABLE 3. - Core-drill samples of coal from Mount Pleasant, Utah

| Bed designation | A | B | C | D | E |
|---|---|---|---|---|---|
| Thickness ..... inches: | 68 | 24 | 52 | 60 | 36 |
| Depth ..... feet: | 955 | 1,032 | 1,097 | 1,143 | 1,151 |
| Analysis, as carbonized .. . percent: | | | | | |
| Proximate: | | | | | |
| Moisture ..... | 3.0 | 3.7 | 3.1 | 3.2 | 4.7 |
| Volatile matter ..... | 45.2 | 42.3 | 43.0 | 42.9 | 42.2 |
| Fixed carbon ..... | 45.5 | 48.9 | 45.5 | 45.3 | 43.9 |
| Ash ..... | 6.3 | 5.1 | 8.4 | 8.6 | 9.2 |
| Ultimate: | | | | | |
| Sulfur ..... | .6 | .8 | .8 | .6 | .5 |
| Agglutinating index, ratio 15:1 ..... | 4.5 | 4.8 | 4.5 | 3.5 | 4.4 |
| Yield of coke at 900° C .... percent . | 58.9 | 59.8 | 60.3 | 60.3 | 61.1 |
| Physical properties of coke: | | | | | |
| Apparent specific gravity ..... | .68 | .70 | .74 | .69 | .70 |
| 1-inch tumbler index ..... | 10.4 | 13.8 | 17.7 | 23.6 | 16.1 |
| 11/16-inch tumbler index ..... | 38.9 | 53.0 | 43.4 | 43.8 | 41.2 |
| 1-inch shatter index ..... | 47.0 | - | - | 58.0 | 57.2 |

## Relation of Petrography to Hydrogenation Properties of Iowa Coal

Five representative coals from Appanoose, Boone, Page, Dallas, and Webster Counties, Iowa, were examined microscopically. All of these coals had a fairly high ash and sulfur content and on this ground alone probably would be rejected for large-scale hydrogenation tests. Coal from Mystic bed, Appanoose County, would be most suitable for hydrogenation, as it has a medium concentration of opaque matter and fusain, the components that are difficult to liquefy. The other four coals have a fairly high concentration of these constituents, especially fusain.

## Mineral Matter in Coal

An investigation of the microscopic forms of mineral matter in coal was conducted on more than 3,000 thin sections of coal. These sections were made from more than 100 beds representative of coals in the United States. The rank of the coals that were investigated extended from peat through the low-volatile bituminous.22/

22/ Sprunk, G. C., and O'Donnell, H. J., Mineral Matter in Coal: Mining Cong. Jour., vol. 28, 1942, pp. 20-23, 72. Mineral Matter in Coal: Bureau of Mines Tech. Paper 648, 1942, 67 pp.



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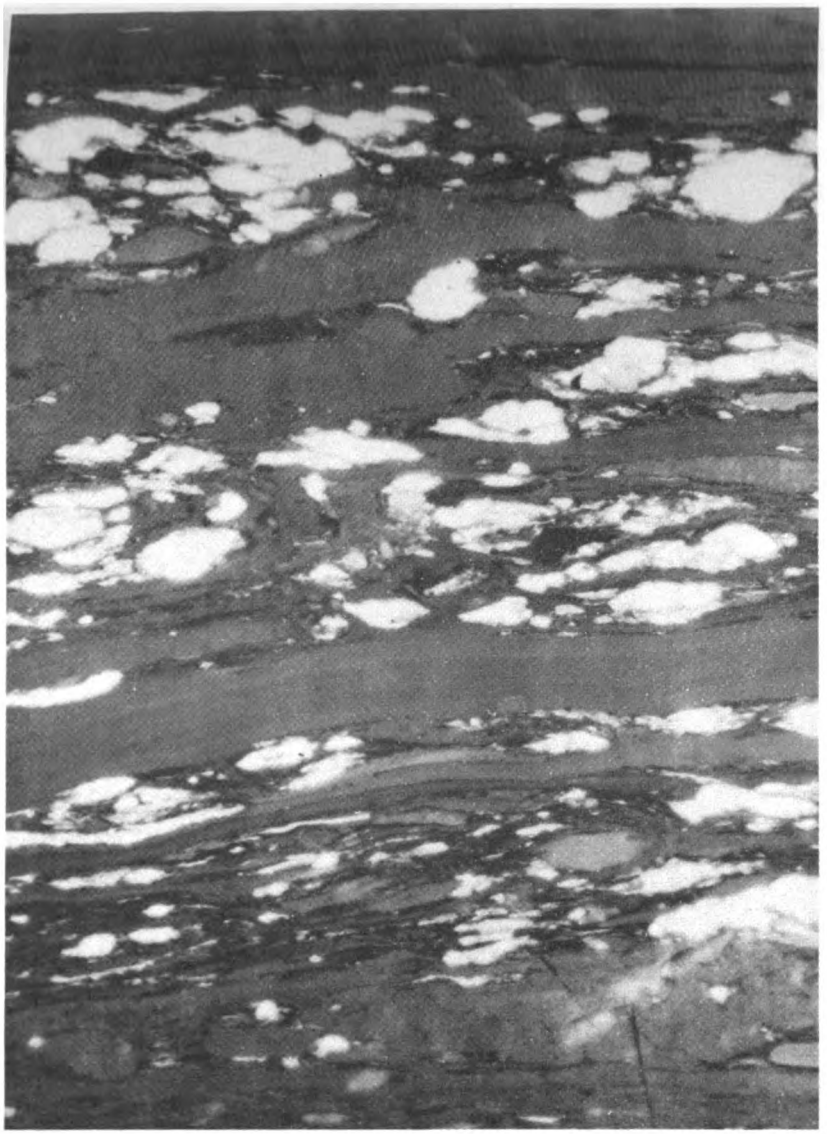

Figure 3.— Irregular white masses of kaolinite lodged in the attrital debris between bands of anthraxylon. X 200.

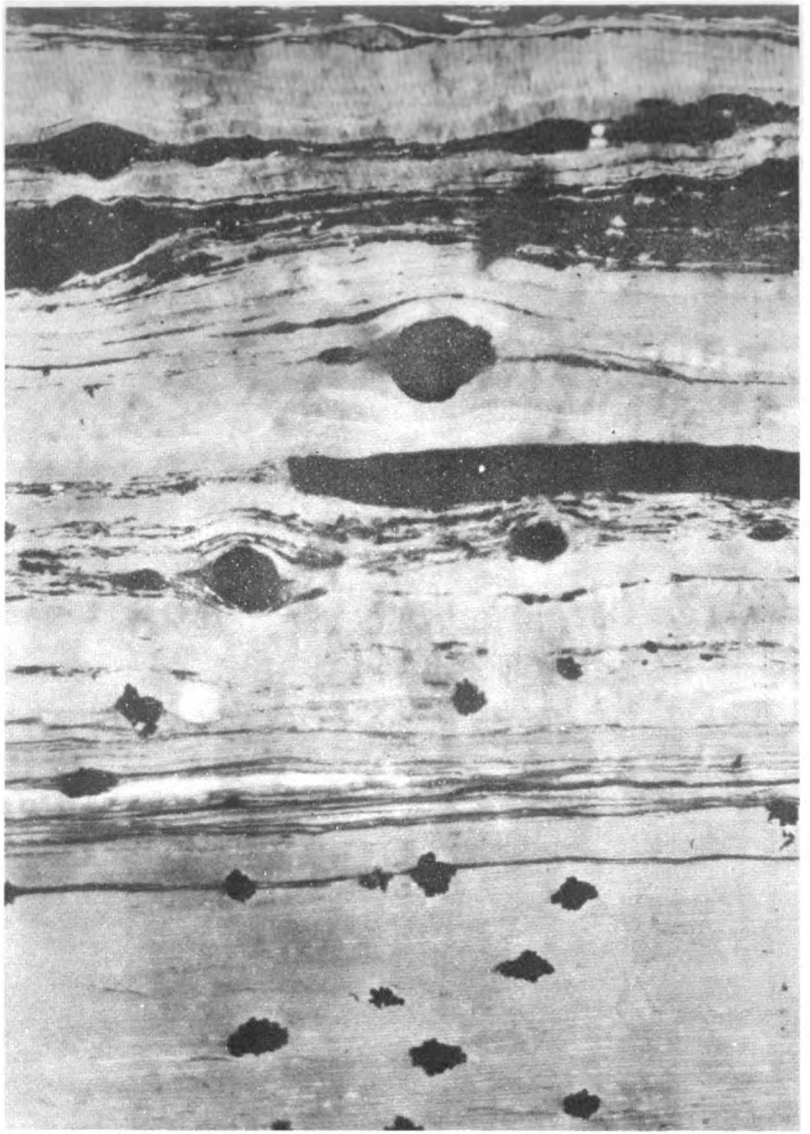

Figure 4.— Irregular to round masses of finely disseminated pyrite embedded in an anthraxylous coal. X 200.

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The investigation was concerned mainly with the microscopic forms of mineral matter in coal. The larger impurities, such as the shale bands, pyrite impurities, ankerites, and materials of similar nature, have been correctly identified and described in several recent publications;[23] but the microscopic forms of mineral constituents are more difficult to identify, and there is a surprising small amount of information in the literature on this type of impurity, although its importance is recognized.

The minerals commonly observed in the thin sections were kaolinite, pyrites, calcite, quartz, and siderite. Several accessory minerals were noted, especially in high-ash coals, bone coals, and shale partings.

Kaolinite occurs in cleat joints, small cracks, fusain, resin rodlets, attritus, or ground mass of coal and in irregular impure masses embedded within the coal. Kaolinite is a common mineral in high-ash coals, bone coals, and a few clay and shale partings. Figure 3 shows typical masses of white kaolinite crystals lodged in the attrital debris between bands of anthraxylon. Under the microscope some of the flocks of kaolinite reveal the typical vermicular structure of kaolinite crystals.

Iron pyrites occur in lenses and bands, balls or nodules, veins, pyritized fossil, and finely disseminated particles. A large part of the total pyrites in coal occurs in the finely disseminated form illustrated in figure 4.

Calcite exists as veins in coal, particularly in the cleats and fractures; it is found also in fusain and in the ground mass of calcareous clay and shale partings.

Siderite occurs as nodules and as impure lenses and bands. Many of the nodules are miniature coal balls; that is, they contain petrified or carbonized plant material. Similarly, as in kaolinite and calcite, siderite may occur as fillings in the cavities of fusain and as small veinlets within the coal mass.

Quartz is especially common in high-ash coals and bone coals. The quartz grains occur mostly in the attrital debris along with such constituents as spores, resins, opaque matter, woody fragments, and leafy tissues.

Petrographic study of mineral matter in coal will have practical adaptation in planning an intelligent program of improving fuels by selective mining or

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[23] Moore, E. S., Coal: John Wiley & Sons, Inc., New York, 1940, 473 pp. Raistrick, A., and Marshall, C. E., The Nature and Origin of Coal and Coal Seams: English Universities Press, Ltd., London, 1939, 282 pp. Stutzer, O., and Noe, A. C., Geology of Coal: University of Chicago Press, Chicago, 1940, 461 pp.



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mechanical cleaning, for the petrographic microscope not only reveals the kind of minerals but also shows the approximate proportion, the grain size, and the exact manner in which they are associated with the coal. When a demand arises for "pure coal" (coal with 1 percent or less ash) the microscope is certain to play an important part in selection of the purest coal. Microscopic examination of mineral matter in coal has already disclosed layers of coal of surprising purity in certain beds.

### Agglutinating-Value Test for Coal

The agglutinating-value test is a small-scale laboratory test intended to give information regarding the coking and caking properties of coal. Investigation has shown that it is extremely sensitive to differences in surface characteristics and shape of various kinds of inert materials used. In particular, sands from various sources give widely different results with the same coal. Individual shipments of sand from the same source also may show marked differences. Investigation of various manufactured materials has not disclosed any that are sufficiently uniform so that different lots can be relied upon to give identical results. In general, silicon carbide is the most satisfactory of the manufactured products investigated. The practical solution of the problem probably is to have someone stock a large amount of well-mixed inert material, such as sand or silicon carbide, and act as a source of supply for all laboratories. Silicon carbide probably is a more generally uniform material than sand.24/

## COAL MINING

## Experimental Coal Mine

### Causes of Falls of Mine Roof

The first phase of the laboratory investigation on the effects of changes of moisture and temperature in mine-roof rocks above the Pittsburgh coal bed was completed. The results indicate that: (1) Exposed rocks of the carbonaceous shale type are affected adversely by variations of humidity in the atmosphere that cause alternate drying and humidification of the rocks: (2) Normal variations of temperature have little or no effect on the strength and behavior of the rocks; (3) proper application of certain asphaltic or coal-tar-base paints greatly reduces the interchange of moisture between air and rocks and has a beneficial effect on the behavior of the roof; (4) reduction of changes of humidity in the air by some form of air conditioning may be of value in reduc-

24/ Selvig, W. A., and Ode, W. H., Inert Material for Agglutinating-Value Test of Coal: Fuel, vol. 21, 1942, pp. 46-51.



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ing these difficulties in some mines. The work was extended to include rocks from three mines in West Virginia. The results of these tests did not modify the general conclusions but showed that a wide range of susceptibility to changes of moisture is to be expected.25/

Operators have shown much interest in methods of preventing falls caused by changes of humidity, and several have adopted the practice of painting roofs in entries, seemingly with good success; at one mine in West Virginia an air-conditioning system was installed to reduce the deposition of moisture on the roof during the summer.

## Multiple-Shift Mechanical Mining

Loading coal mechanically on more than one shift is advantageous, but proper precautions should be taken to preserve the safety of operations. Large investment is required to equip a mine for mechanical mining, and if the daily output can be produced over two or more shifts with the same equipment the capital charge per ton is lower.26/

Rapid extraction from a given area by multiple shifting should result in greater recovery, that is, in conservation of coal resources. Roof conditions cause less trouble where extraction is accelerated, as the coal is removed before the full effects of roof action become operative. The rapid development of fresh faces of the coal bed, however, increases the hazard due to accumulation of dust and increased bleeding of inflammable gas into working places. Mines considered nongaseous because of slow advance of the working faces in hand-loading methods may produce dangerous quantities of gas when advance is rapid under mechanized operations. This hazard should be recognized and proper precautions taken to safeguard the men. It is important to provide the same amount of supervision on all shifts. All working places should be adequately rock-dusted.

The thickness of coal beds has an important influence upon the output of loading machines. This study indicated that the rated capacity of loading machines is rapidly approached with increased thickness of bed. Larger tonnages per cut from thicker beds result in fewer changes of working place, and more time is made available for loading. There is more coal per linear foot of face, and the time required for maneuvering machines is lessened.

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25/ Hartmann, Irving, and Greenwald, H. P., Effect of Changes in Moisture and Temperature on Mine Roof: 1. First Report on Strata Overlying the Pittsburgh Coal Bed: Bureau of Mines Rept. of Investigations 3588, 1941, 40 pp.

26/ Toenges, Albert L., and Maize, Earl R., Multiple-Shift Mechanical Mining in Some Bituminous-Coal Mines. Progress Report 3: Bureau of Mines Inf. Circ., 7178, 1941, 43 pp.



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An advantage is indicated for loading coal by mobile loading machines onto conveyors in moderately thin beds where the roof does not require excessive timbering. This practice allows cars to be loaded in trips on a brushed entry. Thus, larger cars can be used than is possible if cars were taken into rooms for loading; or a number of small cars can be loaded as a unit, and the time lost in changing a large number of individual small cars is reduced. The use of a hopper at the inby end of the conveyor at one mine reduces spillage at the loading point and lessens the amount of coal that must be shoveled by hand. The use of this hopper also increases the area into which the rear conveyor of the loading machine discharges, thus increasing effective loading time and decreasing the time lost in maneuvering the rear conveyor.

The atmosphere in the working place is freer from dust where water is used on the coal before cutting and loading; this practice should also increase the efficiency of miners.

The study indicates that mobile loading machines are best-suited to comparatively level beds with favorable physical conditions. Fragile roof that requires excessive timbering usually results in a slower rate of loading and reduces the tonnage per man because of the additional men required with each crew to maintain the working place in safe condition.

Conveyors are adapted to working thin beds, especially in mines using a long-wall or long-face system of mining. To obtain maximum tonnage per man, enough entry development should be maintained to permit a high proportion of production from walls. Ther should be proper balance between wall and development tonnage.

The advisability of working a mine two shifts a day to obtain optimum results is recognized. For safety of operation, however, the same quantity and quality of supervision should be given on all shifts. The third shift should be used for maintainence of equipment, extension of track, timbering. extension of ventilating circuits, and general mine maintenance. The rapid advance of working places that results from mechanized mining on two shifts allows little time during production shifts for permanent mine maintenance. This work can be done more efficiently and economically on the third shift.

## Use of Diesel Locomotives in Mines

For several years the Bureau of Mines has been investigating the use of Diesel locomotives underground in mines and tunnels. At the outset these studies were directed toward assisting the development of a flameproof Diesel locomotive that might be safer than the exceedingly hazardous electric-trolley locomotive. However, recent conditions have broadened application of the investigation. For example, flame-proof Diesel locomotives can be used in



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hazardous areas in ordnance and synthetic rubber plants where sparks from an electric trolley or steam locomotive might increase explosion hazards. Furthermore, the use of Diesel locomotives underground will conserve the strategic materials copper and rubber and in many instances obviate the installation of additional electric generating equipment.

The safe use of Diesel engines underground depends upon: (1) Elimination of the health hazards due to the discharge of harmful and objectionable gases from the exhaust of the engine into the underground workings; (2) elimination of the explosion hazard if unprotected engines were operated accidentally or unknowingly in inflammable atmospheres; and (3) elimination of fire hazards in handling combustible liquids underground.

Studies to determine the effect of different operating conditions on the composition of the exhaust gases produced by Diesel engines[27] indicate that carbon monoxide, oxides of nitrogen, carbon dioxide, aldehydes, soot, and oxides of sulfur are constituents of the exhaust capable of creating harmful and objectionable atmospheres. However, the tests show that under the conditions investigated the health hazards resulting from the discharge of these constituents into the underground atmosphere can be eliminated if adequate ventilation is supplied.

The test results also have been applied to studies of engine performance and to studies of combustion in Diesel engines.[28]

## Equipment for Testing Diesel Engines

In the past year, equipment was installed for studying the operation of Diesel engines in inflammable atmospheres under conditions simulating those that might exist underground. Preliminary tests were made in a program to evaluate operating hazards under such conditions and to develop methods for testing the effectiveness of flame protective devices.

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27/ Elliott, Martin A., Holtz, John C., Berger, L. B., and Schrenk, H. H., Diesel Engines Underground. III. Effect on Exhaust-Gas Composition of Operating Engines in Mixtures of Normal Air and Natural Gas: Bureau of Mines Rept. of Investigations 3584, 1941, 50 pp.

28/ Elliott, Martin A., and Berger, L. B., Studying Combustion inDiesel Engines by Addition of Gaseous Combustibles to Intake: Paper presented before Gas and Fuels Div., Am. Chem. Soc., Memphis, Tenn., April 20-24, 1942: Ind. Eng. Chem., vol. 34, 1942, pp. 1063-1071.



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The equipment for studying the operation of Diesel engines in inflammable atmospheres is illustrated in figures 5 and 6. The essential parts of this equipment are: (1) The testing chamber, known as the Diesel gallery; (2) the blower and duct system for supplying and maintaining an inflammable atmosphere in the gallery; (3) the control room containing the engine controls, gas-control valves, blower control, and dynamometer.

The Diesel gallery in which engines can be operated while completely surrounded by an inflammable atmosphere is a 7- by 7- by 10-foot chamber. The front end is closed by a paper diaphragm covering a 6- by 6-foot opening, as shown at the right in figure 5. Paper diaphragms also close eight 20-by 30-inch openings on the sides and top. The diaphragms rupture and permit escape of burning gases when the contents of the gallery are ignited. Engines can be mounted inside the gallery, and the exhaust gases may be discharged either into the gallery atmosphere or into the outside atmosphere. Similarly the intake air of the engine may come either from the atmosphere in the gallery or from the outside atmosphere.

The inflammable atmosphere surrounding the engine is a mixture of natural gas and air. To keep this mixture inflammable it is necessary to dilute and remove from the chamber exhaust gases discharged by the engine. The blower and duct system for accomplishing this is shown in figure 5. One safety feature of this system is the provision for making the circulating mixture nonflammable before it is discharged into the outside atmosphere.

The engine, blower, and gas flow are controlled from behind a barricade wall, which is the end wall of the control room (the larger structure in figure 5). These controls, as well as the dynamometer and gas-sampling equipment, are shown in figure 6.

Studies of the operation of Diesel engines in inflammable atmospheres have as their objectives: (1) Determination of the conditions under which a Diesel engine will ignite an inflammable atmosphere; and (2) development of methods for testing the effectiveness of flame-protective devices to prevent such ignitions. During the past year, studies were confined to the first of these two aspects of the problem.

Preliminary tests in the gallery showed that the exhaust gases from a Diesel engine could ignite an inflammable natural gas - air atmosphere under certain engine operating conditions. In all tests in which ignition was obtained, the engine was operated at fuel:air ratios on the rich side. These conditions are abnormal for a properly adjusted Diesel engine, but they could obtain either with a malfunctioning engine or if an engine accidentally encountered high concentrations of combustible gas in an underground atmosphere. Ignitions were not obtained when the engine was operated in the range of fuel:air ratios for



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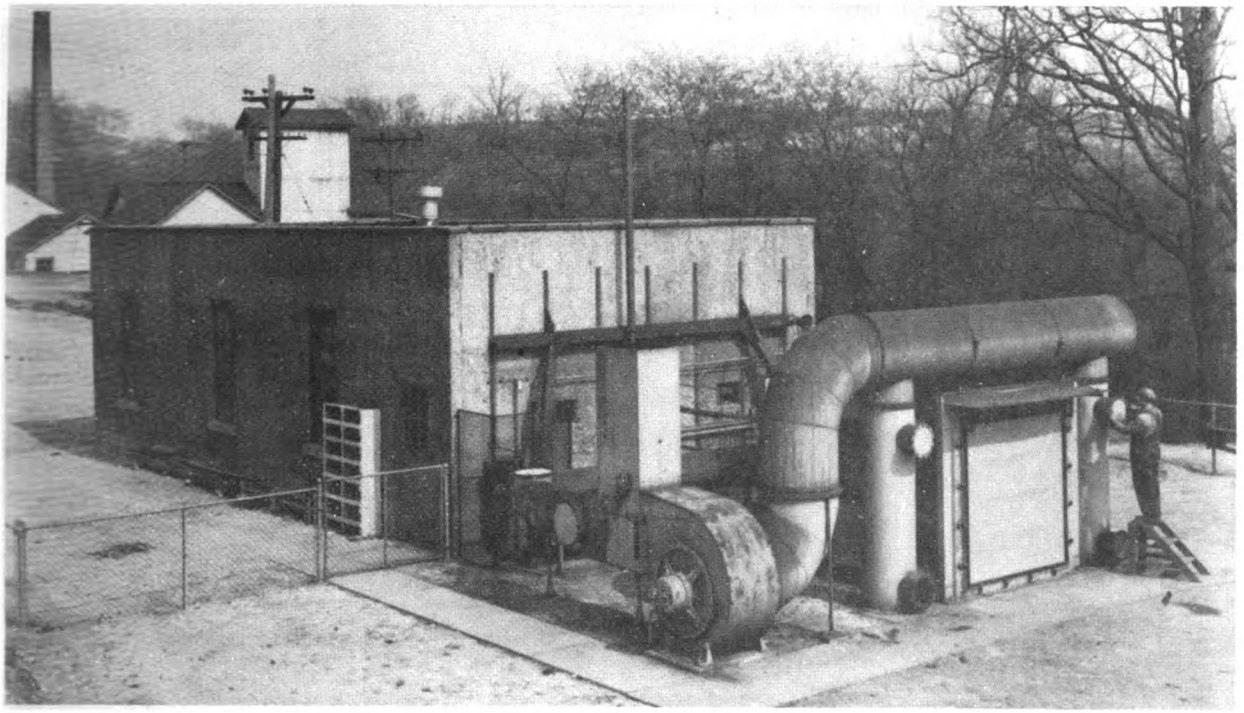

Figure 5.—General view of Diesel gallery and control house.

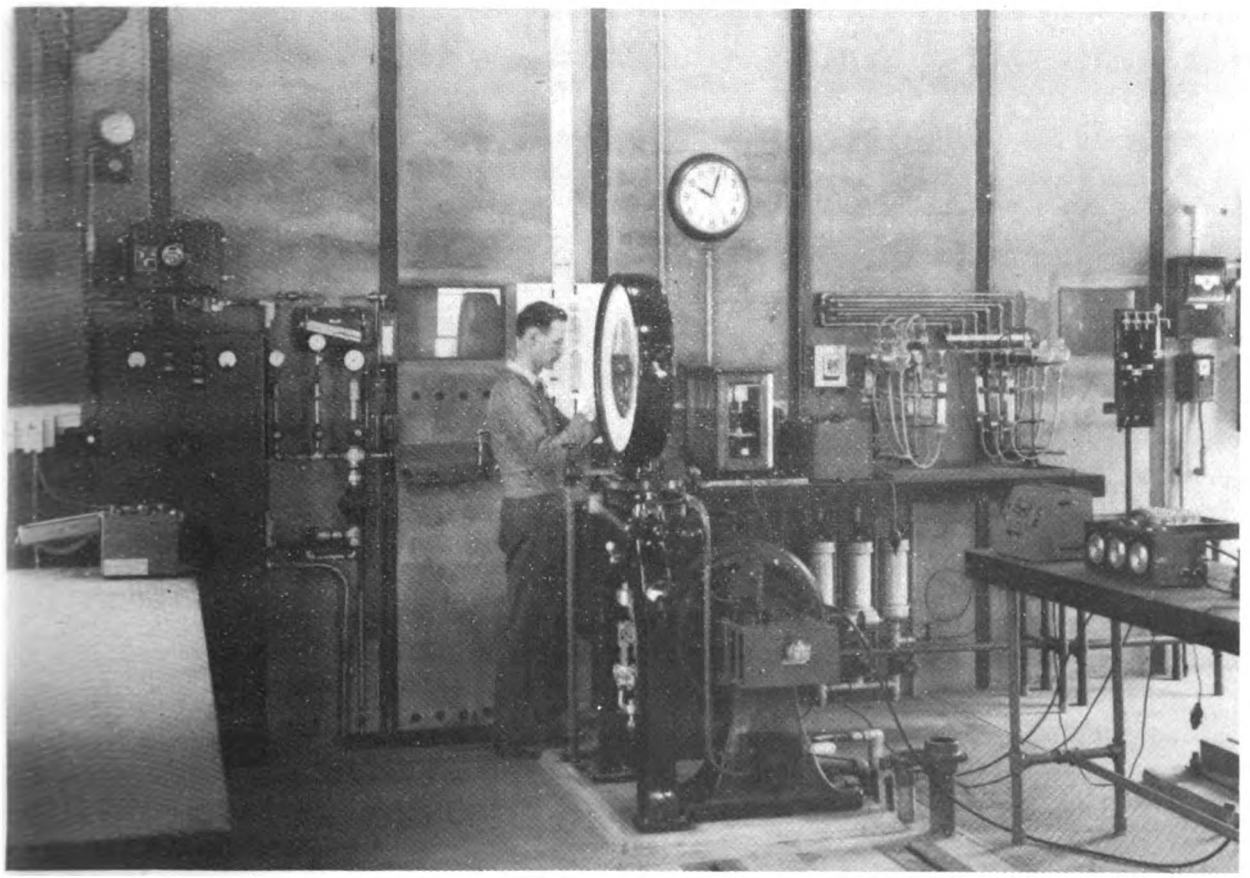

Figure 6.—General view of controls, dynamometer, and gas-sampling arrangements for Diesel gallery.

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which it was originally adjusted by the manufacturer (fuel:air ratios less than 0.045 pound per pound). In this connection it is interesting to note that in one test no ignition was obtained during 2-1/2 hours operation at maximum speed and load.

The operating conditions that caused ignition of the inflammable atmosphere by the exhaust gases from the engine were as follows:

1. The engine was operated at full throttle (maximum quantity of fuel per stroke of fuel pump) and with the intake consisting of normal air taken from outside the gallery. The intake of the engine was throttled progressively, and an ignition occurred when the pressure in the intake manifold was 37 cm. of mercury below atmospheric. Under these conditions the fuel:air ratio was approximately 0.08 pound per pound.

2. The engine was operated at full throttle, and natural gas was added progressively to the intake, which was taken from outside the gallery. Engine speed was maintained constant. The inflammable atmosphere in the gallery ignited when the concentration of natural gas in the intake was between 6 and 7 percent.

Conditions outlined under (1) could occur in practice if the air-cleaner or intake passages of an engine became clogged. Conditions outlined under (2) would occur if an engine operating under load were to encounter an inflammable atmosphere. Ignitions were reproducible by either method, and the results therefore emphasize the necessity of providing flame-protective devices for Diesel engines that might operate in inflammable atmospheres.

As yet no conclusive information is available on the ignition hazard presented by the air intake of the engine or by hot-engine surfaces.

## Consumption of Power at Coal Mines

Increased mechanization of coal mines has emphasized the need for study of the actual consumption of power by the various machines employed in the production of coal and losses in the distribution of power to these machines. These studies are being made in order that hazards, excessive use of power, and high cost of maintenance of equipment resulting from these losses may be analyzed and eliminated. Research on the use of electricity in mines began with a study of individual machines of various types under operating conditions in modern coal mines. Preliminary studies have been made at two mines.[29]

[29] Jones, F. A., Thomas, E., Maize, E. R., Toenges, A. L., An Analysis of Power Consumption at Coal Mines. 1. Preliminary Study: Bureau of Mines Rept. of Investigations 3615, 1942, 20 pp.



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Tests were made on main-line locomotives, mobile loading machines, scrapers, conveyors, and cutting machines. Some of the results of the study are summarized as follows:

1. Dirty haulage roads increase transportation hazards, make poor power returns, cause excessive peak loads and power consumption, and affect the voltage at the face. Moreover, fewer cars are transported per trip, and travel is slower than if the track were clean.

2. Rehandling of coal, necessitated by the system of mining, increases the power consumption of mobile loading machines per ton and causes loss in time and production.

Current supplied at low voltage reduces the rate of loading.

The practice of using conveyors or other equipment as a return is both inefficient and unsafe.

3. The effect of the condition of mechanical equipment on power consumption of scraper hoists is indicated in the tests of development of two down holes.

The length of the walls and size of scoops appear to be maximum for the size of hoist motors used.

4. Losses of power due to poorly insulated cables are shown by one test. These losses result in high operating costs and hazardous conditions.

## Inspection of Electrical and Mechanical Mining Equipment

The Bureau of Mines has two objectives in studies of electrical and mechanical mining equipment:

1. To determine by inspection and test whether the construction of electrical equipment for coal mines will minimize hazards of shock and ignitions of gas and dust by electric sparks.30/

2. To study hazards connected with the operation of mechanical equipment in mines and means for eliminating such hazards to men working with or around this equipment.31/

30/ Ilsley, L. C., Gleim, E. J., and Brunot, H. B., Inspection and Testing of Mine-Type Electrical Equipment for Permissibility: Bureau of Mines Inf. Circ. 7185, 1941, 21 pp.

31/ Ilsley, L. C., Detailed Study of 60-Day Nonfatal Underground Accidents in Pennsylvania Bituminous-Coal Mines During 1939: Bureau of Mines Inf. Circ. 7176, 1941, 36 pp.



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Formal approvals were issued during the year giving permissibility to 23 electrically operated motor-driven machines, including 10 conveyors, 3 loading machines, 3 storage-battery-operated cars for transporting coal, 1 mining machine, 1 truck for conveying mining machines, 1 machinery-moving unit, 1 electric drive for blower, 1 pump, and 2 rock-dust distributors. In addition, numerous extensions of approvals were granted, authorizing changes in permissible equipment.32/

The protection afforded against ignition of gas and dust by a machine in a coal mine depends upon the proper wiring between and assembly of the various electrical units as well as upon the construction of the units themselves. It is therefore the Bureau's policy to approve a machine as an assembly rather than to approve the separate units, such as motors and controllers, used on the machine. However, to encourage the development of such separate units by electrical manufacturers, the Bureau issues "letters of suitability" to manufacturers covering units that meet the inspection and explosion-test requirements. Thus, many assemblers of permissible machines have been saved the expense of designing and building explosion-proof parts. During the year, letters of suitability were issued for five motors, one resistor box, and one push-button station.

During the investigation of complete machines, as well as of individual parts, 1,868 explosion tests on 73 compartments were made in the testing gallery.

The investigation of a dry-cell-type cap lamp in several models was completed, and official approval of this lamp was granted. Examination and test of modified parts of permissible lamps led to extensions of approvals allowing the use of the modified parts. From time to time, studies of field performance of lamps and other permissible equipment are made.33/ These studies are essential to determine the adequacy of laboratory investigations.

The investigation of two models of methane detectors powered by cap-lamp batteries was completed, and formal approvals covering them were granted.34/ Permissible methane detectors belonging to Federal mine inspectors were checked for accuracy.

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32/ Ilsley, L. C., List of Permissible Mine Equipment Approved to January 1, 1942: Bureau of Mines Inf. Circ. 7207, 1942, 35 pp

33/ Hooker, A. B., Field Performance of Permissible Electric Cap Lamps: Bureau of Mines Inf. Circ. 7138, 1942, 11 pp.

34/ Ilsley, L. C., Hooker, A. B. Permissible Methane Detectors: Bureau of Mines Rept. of Investigations 3643, 1942, 10 pp.



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Samples, drawings, and data covering changes in permissible single-shot blasting units were examined, and approvals were officially extended to include those changes. Oscillograph studies of three shunt-wound, multiple-shot blasting machines of the push-down type were made to determine firing characteristics. A paper describing permissible single- and multiple-shot blasting units was published.35/

## Explosives for Use in Coal Mines

To insure continued safe characteristics in permissible mining explosives the Bureau has made 111 chemical analyses, 958 gallery tests, and 673 control tests of a physical nature. There are now 194 explosives and 9 blasting devices (Cardox) on the active permissible lists.36/ The ratio of permissible explosives to black blasting powder used during the year was 1.4:1. The total amount of explosives used for coal mining in this period was approximately 174,000,000 pounds.

### Liquid-Oxygen Explosives

Numerous tests in the open, with many violent igniting agents and small or large cartridges or small quantities of the treated LOX (liquid-oxygen explosives), or ammonia dynamite, showed them to be noninflammable. When large, practical cartridges of treated LOX were tested in the open, some propagating reactions were induced by the most severe igniters employed. When these large cartridges of either treated LOX or ammonia dynamite were tested in drill holes, some detonations resulted from inflammation by large igniters, however, these detonations occurred after delays and warnings that would have induced nearby workmen to leave the danger area.

Although these data corroborate the earlier indications that virtual immunity to practical hazards of ignition may be conferred upon LOX by fire-retardant treatments, they also emphasize the fact that the potentialities common to all high explosives remain as long as such treatments do not destroy the explosive properties of the system. Furthermore, despite the extreme measures employed to induce inflammations in the explosives tested and despite the fact that any such violent igniting actions are unlikely to be met in the field, the occurrence of ignitions with the large charges and the development of detonations from such ignitions under practical confinement in drill holes emphasize that the recommended use of fire-retardant treatments

35/ Ilsley, L. C., Hooker, A. B. Permissible Blasting Units: Bureau of Mines Rept. of Investigations 3593, 1941, 14 pp.

36/ Tiffany, J. E., and Gaugler, Z. C., Active List of Permissible Explosives and Blasting Devices Approved Prior to June 30, 1941: Bureau of Mines Rept. of Investigations 3583, 1941, 23 pp.



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for LOX should for safety be undertaken with no relaxation in the necessary protection of these or any other explosives from hazards of accidental ignition.[37]

Carbonaceous Blasting Accessories

Toxic gases in the products from the detonation of explosives are hazards in blasting underground. Bureau of Mines investigations have shown that the oxygen balance of the explosive is an important factor in controlling toxic gases. This balance is considered in determining the composition of modern metal-mining explosives for blasting underground, and application of the concept has reduced the volume of toxic gases generated. The chemical nature of the material being blasted also influences the composition of the toxic gases produced. Under some conditions of blasting in massive pyrite, unsafe concentrations of sulfur dioxide and hydrogen sulfide have been found. Experiments with the Crawshaw-Jones[38] apparatus have shown that there is an increase in the volume of carbon monoxide in the gaseous products when permissible explosives are detonated in contact with coal dust. Thus, reactive materials of a reducing nature adjacent to explosives loaded in drill holes may decrease the effective oxygen balance of the explosive and cause the volume of toxic gases to increase. Several blasting accessories of reducing nature have been introduced recently for use in coal or metal mines or tunnels. In practice these are loaded adjacent to the explosive, where conditions favor reaction with the products of detonation.

Comparative tests in a Crawshaw-Jones apparatus have shown the effects of three stemmings (including two stemming devices or "blasting plugs" and an impregnated cottonlike substance) and a wooden detonator shield or "safety primer" on the gaseous products from explosives having three widely different oxygen balances. Every accessory caused a marked increase in the volume of gaseous products, particularly of carbon monoxide; this increase was roughly proportional to the weight of the accessory. Other tests in which various weights of two of the carbonaceous accessories were used with a fixed weight of explosive suggest important increases in the total volume of gases, particularly of carbon monoxide, despite the use of relatively low proportions of accessory. It is concluded that the use of such devices in blasting underground may in some instances lead to increased hazards from carbon monoxide. The use of these accessories with a normally low fume metal-mining explosive gave the greatest increase in the volume of carbon monoxide formed. As such

37/ Denues, A. R. T., Practical Fire-sensitivity of Liquid-Oxygen Explosives Treated with Fire-Retardants: Bureau of Mines Rept. of Investigations 3805, 1941, 6 pp.

38/ Crawshaw, J. E., and Jones, G. W., Effect of Coal Dust on the Gases Resulting from Detonating Permissible Explosives: Coal Age, vol. 130, 1926, pp. 906-908.



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explosives are recommended where ventilation is poor, the use of blasting accessories of the type considered may introduce hazards through failure to recognize the drastic alteration imposed by the accessory on the normal gaseous products from the explosive. Broadly, the results show that greater volumes of toxic gases may result when any stemming or other accessory of a reducing nature, capable of reacting in the explosion, is used in loading. Where ventilating conditions are such that toxic gases are not removed promptly, it is recommended that the use of such stemmings or blasting accessories be avoided.39/

## Ventilation of Coal Mines

Underground conditions that require ventilation are general foulness of the mine air caused by the presence of decaying organic matter, emanations from the lungs and bodies of workers and animals, quantities of dust, or low concentrations of toxic or noxious gases.40/

The Bureau of Mines makes the following recommendations regarding the quantity of air to be supplied to underground workers:41/

> The quantity in cubic feet per minute of pure air in any split, circulated through the last open crosscut, should be not less than 200 times the number of men working in the section, and as much more as may be required.
>
> The quantity of air reaching the last open crosscut on any pair of working entries, headings, or gangways, or the maximum inby point of a split should be at least 6,000 cubic feet per minute.
>
> The quantity of air reaching the face of each working place should be at least 200 cubic feet per minute per man employed and as much more as may be necessary to dilute and carry away any inflammable or harmful gases that may be present.
>
> All entries, rooms, panels, or sections that cannot be kept well-ventilated throughout and regularly inspected, or that are not being used for coursing the air, travel, haulage, or the extraction of coal, should be sealed by strong, fireproof stoppings and provided with some means of bleeding-off the gas into the return.

39/ Holtz, John C., and Murphy, E. J., Effects of Carbonaceous Blasting Accessories on Gaseous Products from Explosives: Bureau of Mines Rept. of Investigations 3641, 1942, 24 pp.

40/ Sayers, R. R., Health Hazards from Inadequate Coal-Mine Ventilation: Bureau of Mines Inf. Circ. 7221, 1942, 18 pp.

41/ Bureau of Mines, Tentative Coal-Mine Inspection Standards: Bureau of Mines Inf. Circ. 7204, 1942, 48 pp.



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## Fires in Anthracite Mines

In fighting mine fires, it is necessary to know at the earliest possible moment and continuously thereafter what is happening at the seat of the fire, which may be in a remote or inaccessible area, and also to know what may be expected to result from any proposed combative measure. Based upon knowledge of combustion reactions, a chemist can supply information on such factors as the composition and toxic or asphyxiating properties of the atmosphere in which men may be working, whether the fire is increasing or decreasing in intensity; and its probable temperature, the quantity of air admitted by leakage, and the possibility of explosions in the fire area.42/, 43/

# PREPARATION OF COAL

## Removal of Phosphorus from Washington Coal

Coke of low phosphorus content is required in the electrometallurgical industries recently attracted to the Pacific Northwest by its supply of cheap hydroelectric power. Because little was known about the phosphorus content of Washington coals, the Bureau of Mines and the University of Washington jointly undertook an investigation of its occurrence and its elimination in coal preparation. The work dealt chiefly with the coals of the Wilkeson-Carbonado and Roslyn-Cle Elum fields, for they are the ones likely to be used in making metallurgical coke. All of the coals studied contain, in the as-mined condition, more phosphorus than can be tolerated for certain uses. Moreover, in many of the beds the phosphorus is distributed throughout the coal substance itself and therefore cannot be eliminated by ordinary coal-washing methods. In the No. 2 and No. 3 beds of the Wilkeson-Carbonado field, however, the phosphorus is concentrated largely in heavy impurities, and large-scale laboratory tests demonstrated that the phosphorus content of these coals can be reduced to as low as 0.04 percent by washing - well within the limit specified by all but the most discriminating electrometallurgical industries.

## Drying Subbituminous Coal and Lignite

The Bureau of Mines and the University of North Dakota have cooperated in a technical investigation and economic study of the Fleissner process for drying coal with high-pressure steam. These studies show that American high-

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42/ Scott, G. S., Mechanism of the Steam-Carbon Reaction: Ind. Eng. Chem., vol. 33, 1941, pp. 1279-1285.

43/ Scott, G. S., and Jones, G. W., Application of Chemistry in Combatting Anthracite Mine Fires: Trans. Am. Inst. Min. and Met. Eng., vol. 149, Coal Division, 1942, pp. 207-217.



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moisture coals can be dried successfully to increase their gross heating value 30 to 50 percent. The action of high-pressure steam on coal apparently results in a change of structure and reduction of slacking property.44/, 45/

North Dakota lignite, dried at temperatures corresponding to 400 pounds steam pressure, has a gross heating value of 10,000 B.t.u. per pound. Subbituminous coal, dried under the same conditions, has a gross heating value of 12,000 B.t.u. per pound. The improvement in heating value is proportional to the 0.15 power of the absolute steam pressure.

The estimated cost of a small plant having a capacity of 200 tons per day is $80,000, and the estimated cost of a plant having a capacity of 400 tons per day is $104,000. It is estimated that the cost of drying in the 400-ton plant will be 66 cents per ton of raw coal entering the autoclaves and the cost of drying in the 200-ton plant will be 98 cents per ton of raw coal.

Application of the Fleissner process for drying coal for industrial purposes was estimated by determining the savings in freight rates on the water removed from the coal. These studies indicate that when the cost of drying is 66 cents per ton of raw coal the process will be economical for most markets beyond 250 miles from the mine or where the freight on lignite is more than $1.50 per ton and the freight on subbituminous coal is more than $2.00 per ton.

## Preparation of Pulverized Coal

Many years have been spent in research on grinding, but the results either are expressed in terms of gross power consumed and consequently are influenced by the unknown efficiency of the machinery or are express as an abstract "grindability index." Such data for the most part fall short of the ultimate goal - determination of the net energy consumed in grinding a substance to a specified size. Frequently, in those tests only the most easily ground portion of a certain size of the feed material is ground and this to a size that may be much different from that desired in a commercial operation. Further, the method of grinding employed in some of the tests in no way simulates commercial practice.

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44/ Harrington, L. C., Parry, V. F. and Koth, Arthur, Technical and Economic Study of Drying Lignite and Subbituminous Coal by the Fleissner Process: Bureau of Mines Tech. Paper 633, 1942, 84 pp.

45/ Parry, V. F., Harrington, L. C., and Koth, Arthur, The Preparation of Stable Nonslacking Fuel by Steam-Drying Subbituminous Coal and Lignite: Trans. Am. Soc. Mech. Eng., vol. 64, 1942, pp. 177-183.



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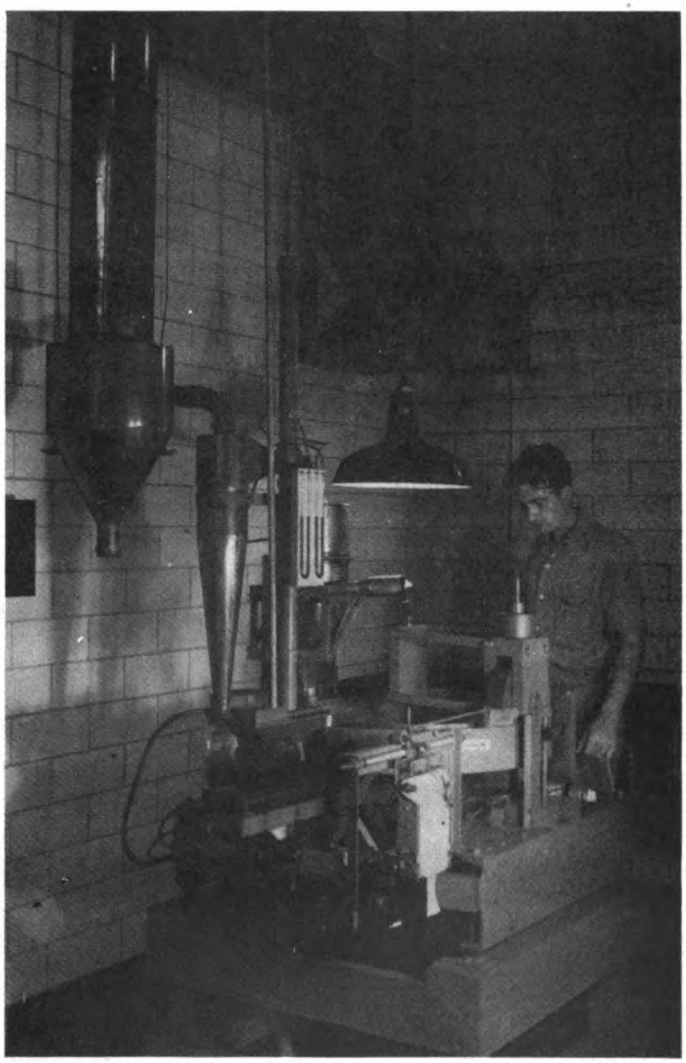

**Figure 7.— Laboratory grinder with force recorder for continuous measurement of net power.**

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A dry pulverizer for test purposes developed will reduce 3/4-inch material to sizes suitable for pulverized-coal burners.[43] Subsieve sizes may be produced, if desired. The method simulates modern commercial practice in that continuous grinding in closed circuit is accomplished by means of air separation and the Cottrell precipitator. This system causes a balanced circulating load to develop, without which accurate power measurement is impossible, particularly on heterogeneous materials. A force recorder that is an integral part of the machine provides for the measurement of the net energy consumed. No corrections for loss due to friction are involved in the power measurement. Operation of the machine has also been very gratifying in the grinding of other materials, such as cement clinker, graphite, kaolin, limestone, mica, oil shale, taconite, and topaz. The ultimate degree of fineness to which the machine is capable of grinding has not been determined, but a relatively coarse muscovite mica has been ground in the pulverizer to a mean particle size of 2.5 microns. This is somewhat finer than the product from the same feed in a commercial "micronizer." It is believed that this energy-measuring pulverizer will point the way to new economics in grinding in the range from about 10-mesh down to and including the "super-fine" sizes. The pulverizer is shown in figure 7.

## Manufacture of Activated Carbon from Coal and Refuse

The utilization of coal and coal refuse as raw material for the production of activated carbon was studied. The carbon was activated for the specific purpose of decolorizing raw-sugar solutions. First the coal is carbonized at 500° C. in a covered iron retort, which allows free escape of volatile matter and minimises oxidation. This preliminary heating drives off the smoke, tar, and oils, which would foul the discharge end of the activating apparatus; it decomposes the complex carbon compounds, drives off the volatile hydrocarbons, and leaves a residue of char consisting largely of carbon. The carbon is considered to be extremely active at the time of its formation, but it is surrounded by volatile decomposition products and instantly absorbs a surface coating of these materials, becoming so saturated that little absorptive power remains. The surface must therefore be cleared to restore the original activity. The cokelike residue is ground to a fine powder in a ball mill and charged into a reaction tube where it is heated to 900° C. in a moving current of steam. This clears the surface of the particles and partly restores their original activity. Activation with steam is viewed as a partial differential oxidation in which the absorbed constituents burn readily while the carbon burns with difficulty and leaves a clean carbon surface.

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43/ Coe, G. D., Delano, P. H., and Coghill, Will H., A Continuously Operating Laboratory Coal Pulverizer that Measures Net Power: Trans. Am. Inst. Min. and Met. Eng., vol. 149, Coal Division, 1942, pp. 231-241.



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Further oxidation of the clean carbon is believed to open and enlarge small pores and capillaries, greatly increasing the total surface.

One interesting point brought out by the investigation is that a water-purification carbon and a sugar-decolorizing carbon differ owing to a greater degree of burning of the latter, which is attributed to the production of larger-diameter capillaries in the sugar-decolorizing carbon. The color bodies in sugar are undoubtedly much larger than the odor-producing bodies in water and so cannot get into small capillaries as easily.

After steam activation the decolorizing power of the carbon is augmented further by an acid treatment, which probably removes soluble salts and much of the ash, increasing the relative amount of pure carbon.

These experiments show that there is an optimum degree of burning for each sample tested and that any additional burning decreases the activity; also, the most active carbons were obtained from the raw materials with the lowest ash content.47/

## STORAGE OF COAL

The possibility of a coal shortage in the winter of 1942-43, due to increased consumption, lack of labor in the mines, and heavy burden on the carriers, led to cooperation between the Bureau of Mines and the Office of Solid Fuels Coordinator for War in a campaign to encourage all consumers to store as much coal as possible during the summer. The Bureau placed engineers at strategic points in the field to give advice on the storage of coal and issued brief papers to explain to consumers that loss of heating value of coals in storage is extremely low and that precautions against slacking need be taken only where subbituminous coal and lignite are stored. Instructions were issued on how to adjust furnaces to compensate for any change in burning characteristics owing to storage and how to avoid spontaneous combustion by following proper procedures in storing coal.48/, 49/, 50/

Research on the effect of oxidation on the coking properties of stored coal is described on page 51 of this report.

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47/ Hertzog, E. S., and Broderick, S. J., Activated Carbon for Sugar Decolorization: Ind. Eng. Chem., vol. 33, 1941, pp. 1192-1198.

48/ Barkley, J. F., Pointers on the Storage of Coal: Bureau of Mines Inf. Circ. 7211, 1942, 7 pp.

49/ Barkley, J. F., Problems Encountered in the Storage of Bituminous Coal: Nat. Eng., vol. 45, 1941, pp. 816-822.

50/ Parry, V. F., Questions and Answers on Storage of Coal in the Rocky Mountain Area: Bureau of Mines Inf. Circ. 7214, 1942, 9 pp.



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# UTILIZATION OF COAL

## Combustion

### Fuel-Engineering Service

Fuel-engineering service rendered to many agencies of the Government included advice on the design and installation of equipment for burning fuels, the buying of the most economical fuels for specific plants, and the economical operation of plants. Acceptance tests were made on new equipment purchased by the Government. Greatly increased consulting advice was rendered on the changing from oil to coal fuel at many plants, the large-scale storage of coal, and the selection and buying of equipment with respect to obstacles interposed by the system of priorities.

### Conditioning of Feed Water for Boilers

In the year ended June 30, 1942, water analyses and recommendations based thereon were made for 3,296 samples of feed water from boiler plants operated throughout the United States by various Government agencies, as compared with 1,045 samples analyzed in 1939, 1,360 samples in 1940, and 1,375 samples in 1941. Reports were made on analyses of 8 boiler compounds and 18 boiler scales, sludges, and deposits. Surveys were conducted at several plants to determine the correct treatment for feed water. At other plants, testing laboratories were installed and engineers instructed in the testing of feed water. Other consulting services on feed water were rendered to Government agencies as required.

### Air Pollution and Smoke Abatement

The literature on pollution of the atmosphere by smoke and other dusts was reviewed, and bibliographies were prepared.51/

During a period when smoke abatement is secondary to maximum utilization of industrial facilities, municipal smoke inspectors are well-qualified, by their familiarity with the facilities in the regions they serve, to assist in solving problems of storage and efficient burning required to prevent a shortage of coal.52/

51/ Bureau of Mines Fuel Economy Service, Bibliography of Papers on the Determination of Dust Fall, Bibliography of Papers on the Determination of Atmospheric Dusts, and Bibliography of Papers on the Determination of Atmospheric Sulfur Dioxide: Smoke Prevention Assoc. America, Inc., Manual of Ordinances and Requirements, 1941, pp. 169-172.

52/ Barkley, J. F., How Smoke Regulation Departments Can Assist in the War Project of the Control, Allotment and Conservation of the Nation's Coal: Proc. 36th Ann. Convention, Smoke Prevention Assoc. America, Inc., 1942, pp. 125-127.



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Physical and Chemical Properties of Coal Ash as Related To Clinkering and Slagging.

The study of the action of coal ash at high temperatures has been continued, with particular emphasis on the difficulties in modern large furnaces burning pulverized coal, such as are used for generating power in central stations. One of the major problems is control of the deposition of slag on the heat-absorbing surfaces. Because the adherence of slag to such surfaces may seriously affect the rate of transfer of heat, knowledge of the properties of coal-ash slag under the conditions in actual installations is indispensable. Also, the problem of removing ash as molten slag is not satisfactorily solved in all cases, and the formation of clinker in fuel beds is not fully understood. In cooperation with the American Society of Mechanical Engineers Special Research Committee on Furnace Performance Factors, a program correlating the laboratory data on coal-ash slags with the actual behavior of the ash in furnaces has been begun as an aid to the design and operation of furnaces.

A new difficulty in operating these furnaces which has recently attained serious proportions is the loss of metal from wall tubes or superheater tubes by corrosion, apparently from contact with coal-ash slags or some constituent evolved from them. Cooperative investigation has been instituted with the Combustion Engineering Co. to determine the mechanism of the reactions leading to this external corrosion of furnace wall tubes or of superheaters. This condition, recognized for the first time early in 1942 as clearly connected with the chemical characteristics of the slag, has been responsible for numerous boiler outages. An early identification of the causes and the development of a complete remedy is imperative to prevent further serious interruptions in power generation.

Density of Slag. - Measurements of the density of molten slags have been made over a wide range of composition. The temperature coefficient is small, the density decreasing about 0.005 for each 100° F. increase in temperature above the liquidus temperature. The density of coal-ash slags is shown to depend on composition and increases with increase in the total content of equivalent $Fe_2O_3$ in the slag; densities range from 2.45 to 3.00. These data are useful for computing the kinematic viscosity of slags and for estimating the weight of slag in a given volume at high temperatures, as, for example, in a bed of molten slag of known dimensions.

Burning Solid Fuels on Traveling Grates

Fuel entering the furnace on a chain-grate stoker, is ignited by three methods: (1) By conduction of heat from the existing fuel bed; (2) by recirculation of burning particles of fuel in the stream of gas above the fuel bed, the burning particles dropping onto the surface of the entering fuel; and (3) by radi-



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ation from hot surfaces of the furnace. During the past year, the investigation of traveling grates has been concerned primarily with the third phase. Attempts to measure the true temperature of the radiating surfaces supplying heat to the fuel bed were not successful, therefore it was necessary to measure directly the quantity of heat transferred by radiation, and a radiometer was designed and constructed for this purpose. It is possible to relate the time required for initial ignition of the surface of the fuel bed as a function of size or composition of the fuel, the rate of supply of air, or the temperature of preheat for specified rates of transfer of heat to the fuel surface. Once surface ignition is complete, the rate of travel of the plane of ignition to the grates is the factor requiring measurement, and the radiometers can be withdrawn to protect them from the high temperatures that are reached in the furnace.

Since ignition must take place before combustion can occur, the time required for ignition is one of the most important variables in fixing the combustion rate obtainable with a given fuel in a specified installation.

An anthracite, washed to produce fractions of varying ash content, has been studied in the crossfeed furnace. An increase in ignition temperature with increase in ash content was observed; although initial ignition of a few isolated particles took place at about the same time for each coal, complete ignition and the progress of ignition through the fuel bed were slower as the ash increased.

Combustion of Coal in Residential-Type Mechanical Stokers

A study was made of the burning characteristics of eight Washington coals when fired on a domestic, ash-remover-type, underfeed stoker installed in a standard hot-water boiler comprising six vertical, cast-iron sections. Twenty-one heat-balance trials were made to determine the effect of variations in ash-softening temperatures and in caking properties on the suitability of these coals as fuels for the ash-remover-type stoker. The trials showed that certain coals, previously found to be unsuitable for burning on the standard underfeed stoker because of their high ash-softening temperatures, burned efficiently and without mechanical difficulty on the ash-remover-type stoker. These coals were characterized by their high ash-softening temperatures and absence of agglutination or caking. Those giving satisfactory results had ash-softening temperatures higher than 2600° F. and no caking properties. Clinker from coals with ash-softening temperatures lower than 2600° F. disrupted the fuel bed while being pushed from the retort by the scraper arms of the ash remover and in addition caused excessive grinding noise in the ash-remover mechanism. Coals with agglutinating values, even as low as 100 grams breaking strength (Marshall-Bird method), could not be burned efficiently because of a high loss of unburned carbon in the ashes.



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Physical Chemistry of Combustion Processes

A detailed experimental study was made of the combustion of hydrogen, including the three explosion limits and the nonexplosive region of the reaction. This investigation resulted in clearer understanding of the important chemical stages of the process and in application of this knowledge to other combustion processes, such as that in flames and in the internal-combustion engine.

The variables investigated for the hydrogen-oxygen reaction were: Temperature from about 400° to 600° C.; pressure (from a few millimeters of mercury to about 2 atmospheres); mixture composition, including addition of the inert gases nitrogen, helium, argon, carbon dioxide, and water vapor; size and nature of the surface of the reaction vessel; and nature of the surfaces of pyrex, quartz, boric acid, potassium chloride, barium chloride, sodium tungstate, potassium tetraborate, and metaborate being studied. The study of the effect of various surfaces showed that the erratic behavior of the reaction in clean quartz or pyrex vessels can be eliminated by coating with any polar compound, such as potassium chloride. Subsequently, the quantitative aspects of the reaction were studied in salt-coated quartz and pyrex vessels, and this work has led to a reaction mechanism that satisfactorily describes the results.53/, 54/ Kinetic equations derived from this mechanism make it feasible to calculate explosion limits and reaction rates in excellent agreement with experimental values over a wide range of conditions.

A review was made of the experimental side of combustion in engines, and methods of temperature and pressure measurements were suggested. The mechanism of engine knock was discussed, and a new method of rating fuels outlined, which is based on the determination of ignition lag, characteristics of the fuel, and the separate determination of engine characteristics.55/

A study was made of the important factors involved in determining the stability of stationary flames; the results of this work have been collected in manuscript form to be presented at the September meeting (1942) of the American Chemical Society and subsequently published.56/ The conditions for

53/ Heiple, H. R., and Lewis, B., The Reaction between Hydrogen and Oxygen: Kinetics of the Third Explosion Limit: Jour. Chem. Phys., vol. 9, 1941, pp. 584-590.

54/ von Elbe, Guenther, and Lewis, Bernard, Mechanism of the Thermal Reaction between Hydrogen and Oxygen: Jour. Chem. Phys., vol. 10, 1942, pp. 366-393.

55/ Lewis, Bernard, The Experimental Side of Combustion Research in Engines: Frontiers of Science: Interscience Publishing Co. (in press).

56/ Lewis, Bernard, and von Elbe, Guenther, Stability and Structure of Burner Flames: Jour. Chem. Phys., vol. 11, 1943, pp. 75-97.



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stability of the flame are found at the base of the flame cone where cooling by the rim of the orifice and interdiffusion with the surrounding atmosphere affect the burning velocity. The limiting gas velocity for blow-off or flash-back is proportional to the cube of the tube diameter from which it follows that the occurrence of these phenomena is determined by the velocity gradient of the gas stream near the tube wall.

By means of fine particles of magnesium oxide introduced into a gas-air stream illuminated by a light beam, the flow pattern of the gas as it emerges from the orifice and passes through the luminous flame cone into the flame envelope was obtained photographically. The velocity of the stream over the cross section was ascertained by stroboscopic means. The temperature distribution in the flame was measured by coloring the central portion with sodium and employing the spectral line-reversal method. Finally, flow pattern and temperature distribution were correlated.

## Carbonization

A survey of the coke industry at the end of 1941 showed construction under way or under negotiation by 13 iron and steel companies for a predicted increase of at least 3,000,000 tons and probably 3,000,000 tons in annual coke production. In addition to metallurgical coke, large supplies were needed for synthetic ammonia plants.[57]

The complete evaluation of a coal for coke and gas making requires a considerable number of tests on a large, truly representative sample. The scale of test must be sufficient to yield enough carbonization products for complete examination and not so large as to be unwieldy.[58] The complete series of carbonization tests, as made by the Bureau, involves carbonization at low, medium, and high temperatures, that is, the whole range of temperature covered by industrial practice. The results show the yield and quality of all products of carbonization, the effect of blending the coal with other coals, and the effect of weathering the coal on the yield and quality of products. Weathering usually results in weaker coke and lower yields of other products. In addition, the pressure exerted on oven walls is determined. Beyond a certain maximum pressure exerted during coking, the walls of coke ovens will be ruined. It is now proposed to introduce an additional test consisting of preheating the coal charged in the ovens to establish the effect on coking properties and the possibility of shortening the time of coking.

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57/ Fieldner, A. C., Processing and Carbonization of Coal: Min. and Met., vol. 23, 1942, pp. 103-104.

58/ Fieldner, A. C., and Davis, J. D., Gas-, Coke-, and Byproduct-Making Properties of American Coals and Their Determination: Bureau of Mines Mon. 5, 1934, $1.50. (May be obtained only from the American Gas Association, 420 Lexington Ave., New York City.)



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During the year full reports were published on work completed during the previous year on coals from the No. 1 bed in Crittenden County, Ky.;[59] Powellton bed in Logan County, Va.;[60] Lower Hignite bed in Bell County, Ky.;[61] Bakerstown bed in Tucker County, W. Va.;[62] and the Henryetta bed in Okmulgee County, Okla.[63]

A descriptive index of the coals that have been tested in this survey was published.[64] This includes analyses and biblographic references on 66 coals

Coals that have been tested cover a wide range in rank and type, but carbonizing properties cannot be correlated closely with rank and type; accordingly, if more definite information is required, individual coals must be tested.[65]

Coals on which complete series of tests were made during the year were: Bevier bed, from No. 18 mine, Cherokee County, Kans.; Thick Freeport bed, from Hamar mine, Allegheny County, Pa.; and McAlester bed, from Dow No. 10 mine, Pittsburg County, Okla. Coal from the Hartshorne bed, No. 17 mine

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59/ Davis, J. D., Reynolds, D. A., Brewer, R. E., Sprunk, G. C., and Schmidt, L. D., Carbonizing Properties and Petrographic Composition of No. 1 Bed Coal from Bell No. 1 Mine, Sturgis, Crittenden County, Ky., and the Effect of Blending This Coal with Pocahontas No. 3- and No. 4-Bed Coals: Bureau of Mines Tech. Paper 628, 1941, 45 pp.

60/ Davis, J. D., Reynolds, D. A., Sprunk, G. C., and Holmes, C. R., Carbonizing Properties and Petrographic Composition of Powellton-Bed coal from Elk Creek No. 1 Mine, Emmett, Logan County, W. Va., and the Effect of Blending this Coal with Pocahontas No. 3- and No. 4-Bed Coals: Bureau of Mines Tech. Paper 630, 1941, 45 pp.

61/ Davis, J. D., Reynolds, D. A., Sprunk, G. C., and Holmes, C. R., Carbonizing Properties and Petrographic Composition of Lower-Hignite-Bed Coal from the Atlas Mine, Middlesboro, Bell County, Ky., and the Effect of Blending This Coal with Pocahontas No. 3- and No. 4-Bed Coals: Bureau of Mines Tech. Paper 634, 1942, 47 pp.

62/ Davis, J. D., Reynolds, D. A., Sprunk, G. C., and Holmes, C. R., Carbonizing Properties and Petrographic Composition of Bakerstown-Bed Coal from No. 23 mine, Coketon, Tucker County, West Virginia, and the Effect of Blending This Coal with Pittsburgh-Bed (Warden Mine) Coal: Bureau of Mines Tech. Paper 644, 1942, 46 pp.

63/ Davis, Joseph D., and Reynolds, D. A., Carbonizing Properties of Henryetta-Bed Coal from Atlas No. 2 Mine, Okmulgee, Okmulgee County, Okla. Oklahoma Geol. Survey, Mineral Report 12 (Prelim. Rept.), in cooperation with Bureau of Mines, 1941, 6 pp.

64/ Wilson, J. E., and Davis, J. D., Index of Coals Tested in the Bureau of Mines Survey of Carbonizing Properties of American Coals: Bureau of Mines Tech. Paper 637, 1942, 10 pp.

65/ Davis, J. D., Selection of Coals for Coke Making: Bureau of Mines Rept. of Investigations 3601, 1942. 29 pp.



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LeFlore County, Okla., was used in blends with the McAlester coal. In addition, less extensive series of tests were made to obtain pertinent information regarding the coking properties of coals from Utah, Colorado, and Wyoming.

All the coals on which work was done during the year are listed with their analyses in table 4. They are referred to in the text by number and bed.

TABLE 4. - Analyses of coals, as carbonized[1/]

Coal 28 - Pittsburgh bed, Warden mine, Allegheny County, Pa.
Coal 56 - Pocahontas No. 3 bed, Buckeye No. 3 mine, Wyoming County, W. Va.
Coal 59 - Upper Freeport bed, Morgantown district, Monongalia County, W. Va.
Coal 60 - Lower Freeport bed, Eastern Indiana County, near Cambria County, Pa.
Coal 61 - No. 1 bed, Bell No. 1 mine, Crittenden County, Ky.
Coal 64 - Bakerstown bed, No. 23 mine, Tucker County, W. Va.
Coal 67 - Taggart bed, Nos. 30 and 31 mines, Harlan County, Ky.
Coal 68 - Henryetta bed, Atlas No. 2 mine, Okmulgee County, Okla.
Coal 70 - Upper Hartshorne bed, Quality mine, Sebastian County, Ark.
Coal 71 - Bevier bed, No. 18 mine, Cherokee County, Kans.
Coal 72 - Thick Freeport bed, Harmar mine, Allegheny County, Pa.
Coal 73 - McAlester bed, Dow No. 10 mine, Pittsburg County, Okla.
Coal 75 - Pocahontas No. 3 bed, McDowell County, W. Va.
Coal 124 - Lower Sunnyside bed, Columbia mine, Utah.
Coal 125 - Lower Sunnyside bed, Sunnyside mine, Utah.
Coal 127 - Horse Canyon mine, Emery County, Utah.
Coal XP24 - Beckley bed, part of foundry mix, Domestic Coke Corporation.
Coal XP25 - Pittsburgh bed, part of foundry mix, Domestic Coke Corporation.
Coal XP26 - 50 percent Beckley bed and 50 percent Pittsburgh bed.

| Coal No.[2/] | Dry, mineral-matter-free, fixed carbon | Proximate, percent | | | Ultimate, percent | | | | | | Heating value, B.t.u. per lb. | Softening temperature of ash, °F. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Moisture | Volatile matter | Fixed carbon | Ash | Hydrogen | Carbon | Nitrogen | Oxygen | Sulfur | | |
| 28 | 62.6 | 1.8 | 35.1 | 57.7 | 5.4 | 5.3 | 79.0 | 1.6 | 7.8 | 0.9 | 14,140 | 2,740 |
| 56 | 81.7 | 1.6 | 17.4 | 74.5 | 6.5 | 4.4 | 83.7 | 1.2 | 3.6 | .6 | 14,400 | 2,780 |
| 59 | 67.7 | 2.8 | 29.3 | 59.6 | 8.3 | 5.2 | 77.0 | 1.4 | 7.4 | .7 | 13,690 | 2,910+ |
| 60 | 73.4 | 2.0 | 24.9 | 66.7 | 6.4 | 5.1 | 81.2 | 1.3 | 5.3 | .7 | 14,310 | 2,840 |
| 61 | 64.4 | 5.4 | 32.3 | 57.3 | 5.0 | 5.5 | 76.5 | 1.3 | 11.0 | .7 | 13,590 | 2,790 |
| 64 | 77.1 | 2.2 | 21.6 | 70.5 | 5.7 | 4.8 | 82.1 | 1.6 | 4.8 | 1.0 | 14,450 | 2,450 |
| 67 | 63.7 | 2.5 | 33.8 | 58.3 | 5.4 | 5.4 | 79.1 | 1.4 | 7.9 | .8 | 14,160 | 2,490 |
| 67B | 68.4 | 2.2 | 29.5 | 62.6 | 5.7 | 5.2 | 80.4 | 1.4 | 6.6 | .7 | 14,190 | 2,710 |
| 67D | 69.2 | 2.3 | 28.8 | 63.1 | 5.8 | 5.1 | 79.7 | 1.4 | 7.2 | .8 | 14,090 | 2,750 |

See footnotes on page 38.



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TABLE 4. - Analyses of coals, as carbonized[1] (Cont'd.)

| Coal No.[2] | Dry, mineral-matter-free, fixed carbon | Proximate, percent: Moisture | Volatile matter | Fixed carbon | Ultimate, percent: Ash | Hydrogen | Carbon | Nitrogen | Oxygen | Sulfur | Heating value, B.t.u. per lb. | Softening temperature of ash, °F. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 68 | 62.0 | 6.8 | 35.9 | 54.0 | 5.3 | 5.6 | 72.5 | 1.8 | 12.7 | 2.1 | 12,970 | 2,040 |
| 68A | 66.3 | 5.6 | 30.4 | 58.4 | 5.6 | 5.3 | 75.0 | 1.8 | 10.5 | 1.8 | 13,230 | 2,060 |
| 68B | 68.2 | 5.3 | 28.7 | 60.0 | 6.0 | 5.1 | 75.3 | 1.7 | 10.1 | 1.8 | 13,280 | 2,020 |
| 68C | 66.2 | 5.7 | 30.5 | 58.4 | 5.4 | 5.4 | 75.0 | 1.8 | 10.7 | 1.7 | 13,280 | 2,050 |
| 70 | 80.9 | 1.6 | 18.3 | 74.9 | 5.2 | 4.5 | 83.9 | 1.8 | 3.9 | .7 | 14,470 | 2,470 |
| 71 | 57.2 | 4.1 | 38.4 | 49.9 | 7.6 | 5.6 | 73.8 | 1.5 | 9.1 | 2.4 | 13,340 | 2,280 |
| 71A | 62.5 | 3.4 | 34.1 | 55.3 | 7.2 | 5.3 | 75.5 | 1.5 | 8.5 | 2.0 | 13,470 | 2,120 |
| 71B | 64.8 | 3.0 | 32.1 | 57.5 | 7.4 | 5.2 | 76.7 | 1.4 | 7.4 | 1.9 | 13,620 | 2,060 |
| 71C | 62.0 | 3.3 | 34.7 | 55.1 | 6.9 | 5.4 | 75.6 | 1.6 | 8.4 | 2.1 | 13,510 | 2,330 |
| 71D | 64.3 | 3.1 | 32.7 | 57.4 | 6.8 | 5.2 | 76.5 | 1.6 | 8.0 | 1.9 | 13,590 | 2,330 |
| 72 | 61.7 | 2.8 | 35.3 | 55.6 | 6.3 | 5.4 | 77.4 | 1.5 | 8.2 | 1.2 | 13,810 | 2,300 |
| 73 | 60.8 | 3.8 | 36.3 | 55.5 | 4.4 | 5.4 | 77.0 | 1.8 | 10.9 | .5 | 13,570 | 2,290 |
| 73A | 65.9 | 3.5 | 31.6 | 59.8 | 5.1 | 5.2 | 77.5 | 1.9 | 9.4 | .9 | 13,620 | 2,300 |
| 73F | - | 3.5 | 34.2 | 57.5 | 4.8 | - | - | - | - | - | - | - |
| 75 | 82.6 | 2.4 | 16.6 | 75.8 | 5.2 | 4.5 | 84.2 | 1.2 | 4.2 | .7 | 14,480 | 2,400 |
| 124 | 57.4 | 5.4 | 38.1 | 50.4 | 6.1 | 5.6 | 72.2 | 1.5 | 13.6 | 1.0 | 12,920 | 2,650 |
| 125 | 57.5 | 4.5 | 38.5 | 51.2 | 5.8 | 5.6 | 73.6 | 1.6 | 12.1 | 1.3 | 13,110 | 2,820 |
| 127 | 56.6 | 4.7 | 39.1 | 50.1 | 6.1 | 5.6 | 72.6 | 1.6 | 13.3 | .8 | 12,880 | 2,370 |
| XP24 | 80.2 | 1.5 | 18.9 | 73.8 | 5.8 | 4.7 | 83.4 | 1.5 | 4.0 | .6 | 14,490 | - |
| XP25 | 61.1 | 2.1 | 36.1 | 55.7 | 6.1 | 5.4 | 78.0 | 1.6 | 8.1 | .8 | 13,970 | - |
| XP26[3] | - | - | 28.1 | 65.9 | 6.0 | - | - | - | - | - | 14,500 | - |

1/ Analyses by H. M. Cooper, chemist, Bureau of Mines.

2/ Coal 67B contains 30 percent Pocahontas No. 3 bed (coal 56); coal 67D contains 30 percent Pocahontas No. 4 bed (coal 57). Coal 68A contains 20 percent and coal 68B contains 30 percent Lower Hartshorne bed (coal 69); coal 68C contains 20 percent Upper Hartshorne bed (coal 70). Coal 71A contains 20 percent and coal 71B contains 30 percent Pocahontas No. 3 bed (coal 56); coal 71C contains 20 percent and coal 71D contains 30 percent Upper Hartshorne bed (coal 70). Coal 73A contains 20 percent and coal 73F contains 10 percent Hartshorne bed (coal 74).

3/ Analyses calculated to dry basis.

Standard Coking Coals

The Advisory Committee on the Bureau of Mines-American Gas Association Survey of American Coals has approved the selection of Pittsburgh high-volatile



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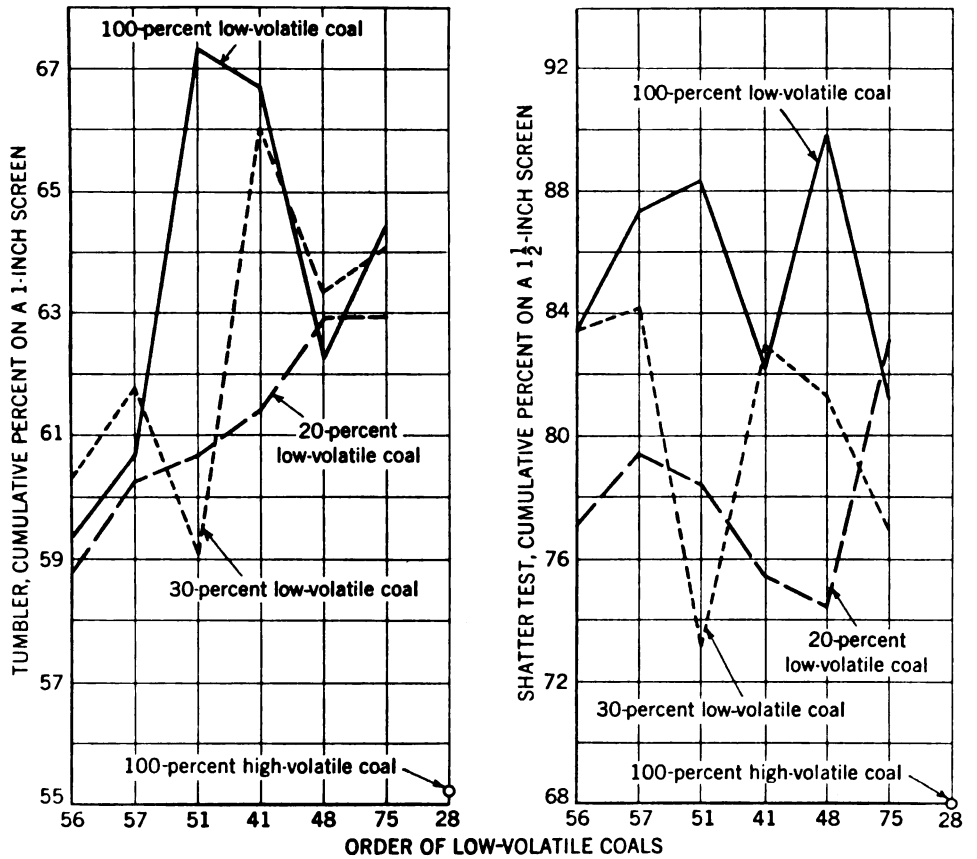


**Figure 8.— Differences in shatter and tumbler indexes of cokes from six low-volatile coals and the effect of blending these coals with a standard high-volatile A coal.**

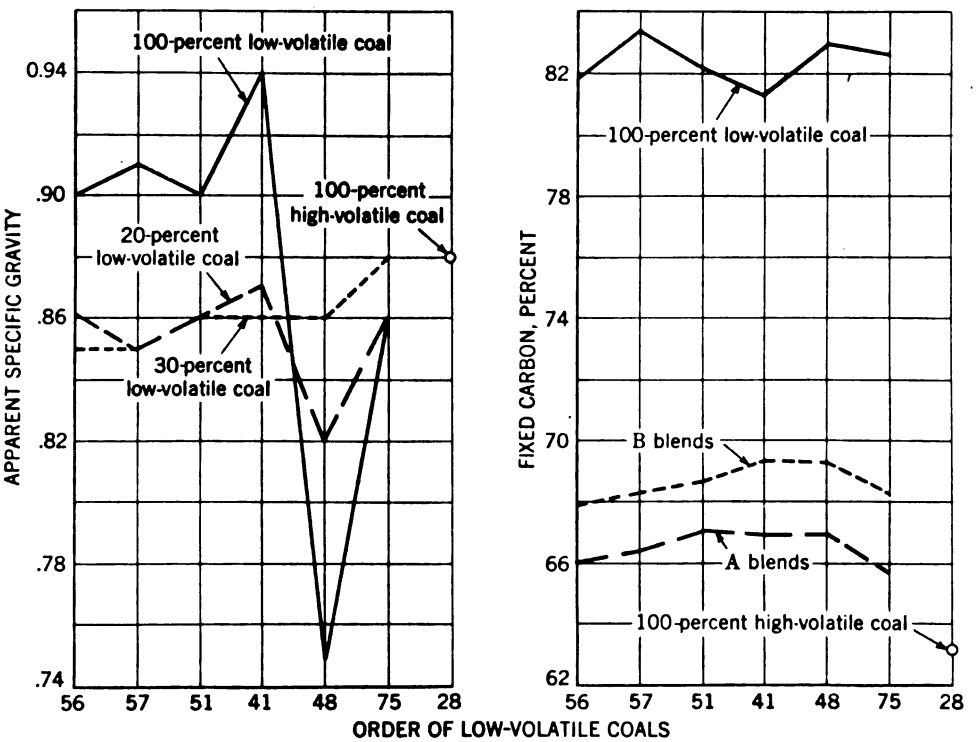


**Figure 9.— Apparent specific gravities and rank of six low-volatile coals and their blends with a standard high-volatile coal.**

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A coal from Sutersville, Allegheny County, Pa. (coal 23) as a standard eastern coking coal of that rank. The committee has also recommended Pocahontas No. 3 (coal 75) from Kimball, McDowell County, W. Va., as a low-volatile blending standard. These coals are to be looked upon as neither the best nor the worst coking coals. For example, figure 8 indicates that the Pocahontas is a good blending coal, and on referring to tables 5 and 6 it can be seen that the Pittsburgh coal is the average high-volatile A coking coal for the East.

The committee has recognized that there is a wide difference in the coking power of eastern and western coals and has recommended Lower Sunnyside coal from Utah as a standard western high-volatile. Lower Sunnyside coal from the Columbia mine was tested in 1932 and is designated as coal (19) of the BM-AGA series. During the year and in connection with a search for coals suitable for making metallurgical coke the Columbia mine was resampled (coal 124), and new tests were made. Also, Lower Sunnyside coals from two additional mines were sampled and tested; the additional mines were the Sunnyside (coal 125) in Carbon County, Utah, and the Horse Canyon (coal 127) in Emery County, Utah. Table 4 shows the analyses of these coals and that of Pittsburgh coal from the Warden mine, and table 5 shows the comparative physical properties of the cokes as tested by A.S.T.M. methods. It is shown that Utah coals are quite different in composition from the Pittsburgh coal and that the latter produces stronger coke. There are some differences in the composition and coking properties of the Lower Sunnyside coals, as judged by the 1-1/2-inch shatter and 1-inch tumbler indexes, but it cannot be said that one is consistently better than another. It is known that this coal changes somewhat in the same mine, as evidenced by differences in Columbia mine samples 19 and 124. It should be observed that the Sunnyside coke is used successfully for smelting iron ore, although it is a weak coke for large, modern blast furnaces.

Average shatter and tumbler properties[66/] were computed for cokes made from coals of different ranks in the 13- and 18-inch retorts at 800° and 900° C. Table 6 summarizes the results. The summary is open to the criticism that all of these tests were applied to only a few coals, particularly those of high-volatile B and C and medium-volatile ranks. As far as the averages may be considered significant, the tables show:

1. The shatter 1-1/2-inch and tumbler 1-inch for cokes made at 800° are higher than for those made at 900°, but the reverse is true for the 1/4-inch tumbler indexes (hardness factor); that is, the 800° cokes are tougher but softer than those made at 900° C.

66/ Reynolds, D. A., and Holmes, C. R., Physical Properties of Cokes from Bureau of Mines-American Gas Association Tests at 800° and 900° C: Bureau of Mines Rept. of Investigations 3350, 1942, 14 pp.



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TABLE 5. - Coking properties of Lower Sunnyside and Pittsburgh-bed coals in the 13-inch BM-AGA retort, 900° C.

| Coal No. | Bed | Mine | True specific gravity | Apparent specific gravity | Cells, percent | Shatter test, cumulative percent upon- | | | | Tumbler test, cumulative percent upon- | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | 2-in. screen | 1-1/2-in. screen | 1-in. screen | 1/4-in. screen | 2-in. screen | 1-1/2-in. screen | 1-in. screen | 1/4-in. screen |
| 28 | Pittsburgh | Warden | 1.86 | 0.84 | 54.7 | 29.6 | 69.7 | 93.7 | 98.1 | 0.0 | 12.9 | 52.9 | 69.3 |
| 19 | Lower Sunnyside | Columbia | 1.92 | .76 | 60.4 | 16.3 | 43.6 | 71.0 | 97.4 | .0 | .0 | 20.9 | 78.4 |
| 124 | do. | do. | - | .74 | - | 8.6 | 34.1 | 75.3 | 93.3 | .0 | .0 | 21.4 | 75.8 |
| 125 | do. | Sunnyside | - | .75 | - | 6.1 | 27.6 | 70.8 | 97.8 | .0 | .5 | 20.0 | 77.5 |
| 127 | do. | Horse Canyon | - | .73 | - | 16.3 | 41.3 | 70.9 | 96.9 | .0 | .0 | 16.7 | 74.4 |



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TABLE 6. - Shatter- and tumbler-test Indexes of 800° and 900° C. BM-AGA cokes from coals of different rank

| | Retort diameter, inches | Rank of coal | | | |
|---|---|---|---|---|---|
| | | High-vol. B & C | High-vol. A | Med-vol. | Low-vol. |
| 800° cokes: 1-1/2" shatter | 13 | 64.2 | 82.7 | 94.7 | 94.5 |
| | 18 | 66.5 | 83.0 | 95.4 | 95.2 |
| | | +2.3[1] | + .3 | + .7 | + .7 |
| 1" tumbler | 13 | 27.0 | 49.5 | 71.7 | 64.7 |
| | 18 | 29.7 | 47.3 | 72.1 | 64.2 |
| | | +2.7 | -2.2 | + .4 | - .5 |
| 1/4" tumbler | 13 | 67.0 | 66.5 | 74.3 | 66.6 |
| | 18 | 67.3 | 66.8 | 74.0 | 66.3 |
| | | + .3 | + .3 | - .3 | - .3 |
| 900° cokes: 1-1/2" shatter | 13 | 52.6 | 64.8 | 78.2 | 77.2 |
| | 18 | 50.1 | 70.4 | 84.6 | 85.1 |
| | | -2.5 | +5.6 | +6.4 | +7.9 |
| 1" tumbler | 13 | 31.8 | 48.2 | 66.6 | 62.0 |
| | 18 | 33.2 | 50.8 | 69.0 | 64.3 |
| | | +1.4 | +2.6 | +2.4 | +2.3 |
| 1/4" tumbler | 13 | 73.0 | 71.8 | 77.4 | 74.7 |
| | 18 | 75.1 | 72.2 | 76.7 | 72.8 |
| | | +2.1 | + .4 | - .7 | -1.9 |
| Number of coals tested at 800°: | | 1 | 13 | 4 | 7 |
| 900°: | | 3 | 25 | 6 | 9 |

[1] + indicates that the 18-inch-retort coke is the best; - indicates that the 13-inch-retort coke is best.

2. Maximum carbonizing temperature has an important effect on coking properties; the effect of size of the testing retort (rate of coking) is not so pronounced, and differences generally favor the 18-inch retort where the rate of travel of the plastic layer is slowest.

## Blending Properties

A new low-volatile coal (coal 75) from the Pocahontas No. 3 bed at Kimball, McDowell County, W. Va., was obtained during the year for future blend tests with eastern and midwestern high-volatile coals. Low-volatile coals



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previously used as blending coals in 20- and 30-percent amounts are as follows:

Coal 56, Pocahontas No. 3 bed, Buckeye No. 3 mine, Wyoming County, W. Va.

Coal 57, Pocahontas No. 4 bed, No. 4 mine, Raleigh County, W. Va.

Coal 51, Washed Upper Kittanning bed, No. 72 mine, Cambria County, Pa.

Coal 41, Beckley bed, Winding Gulf No. 1 mine, Raleigh County, W. Va.

Coal 48, washed Lower Kittanning bed, No. 73 mine, Johnstown, Cambria County, Pa.

The carbonization tests were made in the BM-AGA 18-inch retort at 900° C.

All these low-volatile coals were blended with a standard high-volatile coal from the Pittsburgh bed, Warden mine, Sutersville, Allegheny County, Pa. In figure 8 the coals are arranged in the order of increasing 1-inch tumbler indexes; the same order is used for other curves shown in this figure and also for those shown in figure 9. Table 7 gives the complete shatter and tumbler data, including apparent specific gravities and rank of the coals and blends.

The scale on which the measure of physical properties is given in figure 8 is large, and differences are thus exaggerated. Figure 8 illustrates the following points:

1. None of the other curves follows closely the arbitrary order adopted for the 1-inch tumbler indexes, and the shatter and tumbler indexes do not indicate the same relative strength of the cokes. The latter is not surprising, because in the two tests the forces causing reduction in size of the cokes differ.

2. It is impossible to calculate these properties from a knowledge of the properties of the constituent coals; there are instances where the 20-percent blends are better than the 30-percent blends and also where 100-percent charges of the low-volatile coals produce poorer coke than the blends.

Figure 9 shows wide variation in the apparent specific gravities of the cokes from 100-percent charges of low-volatile coals, although their variation in rank is not large. Variations in rank of the blend cokes are not large, and they follow closely the order in figure 8. Probably the reason for this is the high percentage of high-volatile A Coal in both blends.



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TABLE 7. - Properties of cokes from constituent coals and blends carbonized at 900° C. in the BM-AGA 18-inch retort

| Coal No. | Rank[1] | Apparent specific gravity | Shatter test cumulative percent upon- 2-in. screen | 1-1/2-in. screen | 1-in. screen | 1/4-in. screen | Tumbler test, cumulative percent upon- 2-in. screen | 1-1/2-in. screen | 1-in. screen | 1/4-in. screen |
|---|---|---|---|---|---|---|---|---|---|---|
| 56 | 81.7 | 0.90 | 59.9 | 83.3 | 94.6 | 98.5 | 5.2 | 32.5 | 59.3 | 71.5 |
| 56A[2] | 66.0 | .86 | 45.1 | 77.0 | 94.0 | 98.6 | 2.2 | 25.6 | 58.8 | 71.4 |
| 56B[3] | 67.8 | .85 | 57.6 | 83.3 | 94.7 | 98.4 | 3.4 | 31.4 | 60.3 | 70.9 |
| 57 | 83.3 | .91 | 62.2 | 87.3 | 95.2 | 98.3 | 9.0 | 37.4 | 60.7 | 70.6 |
| 57A | 66.4 | .85 | 46.3 | 79.5 | 94.7 | 98.3 | 3.0 | 31.4 | 60.3 | 71.8 |
| 57B | 68.2 | .85 | 51.3 | 84.1 | 95.2 | 98.7 | 3.2 | 33.9 | 61.8 | 72.8 |
| 41 | 81.3 | .94 | 53.6 | 82.1 | 95.2 | 98.6 | 12.5 | 36.3 | 66.7 | 76.3 |
| 41A | 66.9 | .87 | 36.4 | 75.5 | 94.6 | 98.7 | 4.2 | 29.0 | 61.4 | 72.4 |
| 41B | 69.2 | .86 | 52.7 | 82.9 | 95.9 | 98.7 | 6.0 | 38.9 | 66.0 | 75.4 |
| 48 | 82.9 | .75 | 65.1 | 89.7 | 96.6 | 98.6 | 11.2 | 44.5 | 62.3 | 67.7 |
| 48A | 66.9 | .81 | 39.6 | 74.6 | 93.8 | 98.6 | .9 | 25.7 | 62.9 | 73.6 |
| 48B | 69.2 | .81 | 45.1 | 81.5 | 95.5 | 98.7 | 2.5 | 29.7 | 63.3 | 73.4 |
| 51 | 82.1 | .90 | 66.1 | 88.3 | 96.6 | 98.8 | 10.4 | 38.8 | 67.3 | 74.7 |
| 51A | 67.0 | .86 | 46.6 | 78.5 | 94.7 | 98.5 | 1.1 | 27.4 | 60.7 | 72.5 |
| 51B | 68.6 | .86 | 35.9 | 73.1 | 93.9 | 98.5 | 3.6 | 27.7 | 59.1 | 73.7 |
| 75 | 82.6 | .86 | 58.5 | 81.2 | 95.0 | 98.8 | 7.0 | 35.5 | 64.4 | 74.5 |
| 75A | 65.6 | .86 | 50.0 | 83.0 | 94.9 | 98.4 | 4.4 | 31.4 | 63.0 | 73.1 |
| 75B | 68.1 | .85 | 44.3 | 76.9 | 94.5 | 98.6 | 5.5 | 33.0 | 64.1 | 74.4 |
| 28 | 62.6 | .88 | 33.1 | 68.0 | 93.2 | 98.6 | 1.8 | 20.4 | 55.2 | 71.5 |

1/ Dry, mineral-matter-free fixed carbon.
2/ 20 percent of the low-volatile with 80 percent of the high-volatile coal.
3/ 30 percent of the low-volatile coal with 70 percent of the high-volatile coal.



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From these results it is clear that every low-volatile blending coal must be treated individually as far as the physical properties of the coke are concerned. That is, if it is desired to know these properties within the limits of experimental error, actual tests must be made on experimental cokes. This probably applies also where a standard low-volatile coal is used with different high-volatile coals.

McAlester-Bed Coals

A complete series of BM-AGA tests was made on a sample of McAlester-bed coal (coal 73) from Dow No. 10 mine in Pittsburgh County, Okla. The analysis (table 4) shows that it is a high- volatile A coal of low ash and sulfur content and that the softening temperature of the ash is low at 2,290° F. The main object in testing this coal was to determine whether it could be used to make coke for smelting iron ores and thus supplement Oklahoma reserves of coals of this coking quality. The work was done in cooperation with the Oklahoma Geological Survey. The tests indicate that the coal is poorly coking by eastern standard of metallurgical practice but that its coking power can be improved greatly by blending with low-volatile coals available in Oklahoma; accordingly it may be looked upon as reserve coking coal.

Bevier-Bed Coal

The Bevier- or Limeston-bed coal (coal 71) was obtained from the No. 18 mine at West Mineral, Cherokee County, Kans.; its rank is high-volatile A bituminous. The analysis of the carbonizing sample is given in table 4, and table 8 shows the yields of carbonization products obtained at low, medium, and high carbonization temperatures and also for blends coked at 900° C. in the BM-AGA 18-inch retort. Table 9 gives physical properties of the cokes. This table also shows the average shatter 1-1/2- and tumbler 1-inch indexes for 25 coals in this range of rank previously tested, to serve as a basis of comparison.

Table 9 shows that the shatter index of the coke is almost as good as the average for high-volatile A coals but that the tumbler index is somewhat low; however, it is shown that both can be improved considerably by blending with 30 percent of low-volatile coal. It is assumed that Hartshorne low-volatile coal would be available for the purpose, but probably the Bevier coal coked alone would produce a usable furnace coke were it not for its high sulfur content.



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TABLE 8. - Yields of carbonization products, as-carbonized basis, from Bevier-bed coal

Coal 71 - 100 percent Bevier bed
Coal 71A - 80 percent Bevier bed and 20 percent Pocahontas No. 3 bed (coal 56)
Coal 71B - 70 percent Bevier bed and 30 percent Pocahontas No. 3 bed (coal 56)
Coal 71C - 80 percent Bevier bed and 20 percent Upper Hartshorne bed (coal 70)
Coal 71D - 70 percent Bevier bed and 30 percent Upper Hartshorne bed (coal 70)

| Coal No. | Retort diameter, inches | Carbonizing temperature, °C. | Yields, percent by weight of coal[1] | | | | | | | Yields per ton of coal[1] | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Coke | Gas | Tar | Light oil | Free ammonia | Liquor | Total | Gas, cubic feet | Tar, gallons | In gas | Tar to 170°C. | $(NH_4)2SO_4$, pounds |
| 71 | 13 | 500 | 72.2 | 6.1 | 12.4 | 0.52 | 0.020 | 7.2 | 98.4 | 2,500 | 29.0 | 1.67 | 2.38 | 4.8 |
| 71 | 13 | 800 | 64.3 | 14.8 | 9.6 | 1.31 | .180 | 7.5 | 97.7 | 8,950 | 19.9 | 3.74 | 1.43 | 22.3 |
| 71 | 18 | 900 | 64.2 | 16.7 | 8.5 | 1.57 | .138 | 7.4 | 98.5 | 10,650 | 17.3 | 4.38 | 1.07 | 20.8 |
| 71A | 18 | 900 | 68.1 | 15.3 | 7.1 | 1.35 | .157 | 6.5 | 98.5 | 10,300 | 14.6 | 3.81 | .76 | 20.1 |
| 71B | 18 | 900 | 70.2 | 14.8 | 6.0 | 1.46 | .163 | 6.2 | 98.8 | 10,250 | 12.6 | 4.14 | .63 | 19.9 |
| 71C | 18 | 900 | 67.9 | 15.4 | 6.6 | 1.37 | .166 | 6.1 | 97.5 | 10,400 | 13.8 | 3.86 | .73 | 19.9 |
| 71D | 18 | 900 | 69.7 | 14.9 | 6.2 | 1.30 | .200 | 5.9 | 98.2 | 10,300 | 13.0 | 3.67 | .64 | 22.4 |

1/ Coke, tar, ammonia, and light oil are reported moisture-free; gas is reported as stripped of light oil and saturated with water vapor at 60° F. and under 30 inches of mercury.



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TABLE 9. - Physical properties of coke from Bevier-bed coal

Coal 71 - 100 percent Bevier bed
Coal 71A - 80 percent Bevier bed and 20 percent Pocahontas No. 3 bed (coal 56)
Coal 71B - 70 percent Bevier bed and 30 percent Pocahontas No. 3 bed (coal 56)
Coal 71C - 80 percent Bevier bed and 20 percent Upper Hartshorne bed (coal 70)
Coal 71D - 70 percent Bevier bed and 30 percent Upper Hartshorne bed (coal 70)

| Coal No. | Retort diameter, inches | Carbonizing temperature, °C. | True specific gravity | Apparent specific gravity | Cells, percent | Shatter test, cumulative percent upon- | | | | Tumbler test, cumulative percent upon- | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | 2-in. screen | 1-1/2-in. screen | 1-in. screen | 1/4-in. screen | 2-in. screen | 1-1/2-in. screen | 1-in. screen | 1/4-in. screen |
| 71 | 13 | 500 | 1.51 | 0.69 | 54.3 | 73.9 | 81.4 | 88.5 | 95.4 | 1.9 | 15.8 | 32.3 | 44.9 |
| 71 | 13 | 800 | 1.92 | .79 | 58.9 | 70.5 | 83.5 | 89.7 | 96.6 | 3.8 | 21.9 | 38.0 | 54.2 |
| 71 | 18 | 900 | 1.95 | .80 | 59.0 | 52.6 | 73.2 | 85.1 | 96.3 | 4.6 | 18.0 | 33.9 | 56.7 |
| | | | | | | | 70.4 | | | | | 50.8 | 72.2 |
| Average for 25 high-volatile A coals | | | | | | | | | | | | | |
| 71A | 18 | 900 | 1.92 | .85 | 55.7 | 50.2 | 74.2 | 90.5 | 97.8 | 2.0 | 20.7 | 45.0 | 64.5 |
| 71B | 18 | 900 | 1.95 | .83 | 57.4 | 67.1 | 86.1 | 93.9 | 98.1 | 6.4 | 28.8 | 51.5 | 65.9 |
| 71C | 18 | 900 | 1.91 | .80 | 58.1 | 80.5 | 91.3 | 95.7 | 98.2 | 11.8 | 42.5 | 58.8 | 64.4 |
| 71D | 18 | 900 | 1.93 | .83 | 57.0 | 70.3 | 89.5 | 96.1 | 98.5 | 9.7 | 42.7 | 63.0 | 70.3 |

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Table 8 gives the yields of carbonization products obtained from Bevier coal. The yields of tar and light oil are exceptionally high and that of gas is good. Correspondingly, the yields of coke are low. Probably it would not be practical at present to take advantage of these high yields of volatile products because of the urgent demand for furnace coke. The coke would be used for domestic heating, but the clinkering of the ash would be objectionable. However, ashes of competing domestic cokes in this region might clinker as badly or even worse than that from Bevier coal.

Thick Freeport Coal

The main purpose in selecting this coal for test was to determine whether its coking properties could be improved by blending with Pocahontas low-volatile coal instead of the Lower Kittanning, which has been used up to the present. The Kittanning coal expands more than the Pocahontas, and consequently less of it can be used in blends than of the Pocahontas. The sample was obtained from the Harmar mine near Harmarville, Allegheny County, Pa. Thick Freeport coal from a neighboring mine (Wildwood) had been tested previously, but at that time no blending tests were made.

The analysis of coal from the Harmar mine is given in table 4, and the physical properties of the coke from this coal and from blends with Pocahontas No. 4 are shown in table 10. Physical properties of the 900° coke from Wildwood-mine coal are included for comparison.

The 900° coke from Thick Freeport coal had a 1-1/2-inch shatter index of 73.5 and a 1-inch tumbler index of 52.7, which indicates that this coal is more strongly coking than average high-volatile A coals because the corresponding indexes for 25 high-volatile A coals averaged 70.4 for the 1-1/2-inch shatter and 50.8 for the 1-inch tumbler. Blending with 20 percent Pocahontas coal increased the 1-1/2-inch shatter index to 80.1 and the 1-inch tumbler index to 59.7; the coke from the blend containing 30 percent Pocahontas No. 4 coal was slightly stronger, but the difference shown by these tests is probably not significant. The 2- and 1-1/2-inch shatter indexes of the 500° and 800° coke were higher than those for any other coke shown in the table, including the blends with Pocahontas coal, although the 1-1/2-inch tumbler indexes were lower. The 500° and 800° cokes were made in the BM-AGA 13-inch retort; the 900° cokes, including the blends, were made in the BM-AGA 18-inch retort. The Harmar and Wildwood mines produce high-temperature cokes of almost identical properties.



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TABLE 10. - Physical properties of coke from Thick Freeport-bed coal

Coal 72 - 100 percent Thick Freeport bed, Harmar mine
Coal 72A - 80 percent Thick Freeport bed and 20 percent Pocahontas No. 4 bed
Coal 72B - 70 percent Thick Freeport bed and 30 percent Pocahontas No. 4 bed
Coal 20 - 100 percent Thick Freeport bed, Wildwood mine

| Coal No. | Retort diameter, inches | Carbonizing temperature, °C. | Apparent specific gravity | Shatter test, cumulative percent upon- | | | | Tumbler test, cumulative percent upon- | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | 2-in. screen | 1-1/2-in. screen | 1-in. screen | 1/4-in. screen | 2-in. screen | 1-1/2-in. screen | 1-in. screen | 1/4-in. screen |
| 72 | 13 | 500 | 0.69 | 68.6 | 83.8 | 90.0 | 96.2 | 15.2 | 34.9 | 47.9 | 54.5 |
| 72 | 13 | 800 | .77 | 69.0 | 83.0 | 90.4 | 97.4 | 8.3 | 32.6 | 49.4 | 64.9 |
| 72 | 18 | 900 | .82 | 42.3 | 76.5 | 91.9 | 98.0 | .1 | 18.4 | 52.6 | 71.8 |
| 72A | 18 | 900 | .83 | 49.2 | 80.1 | 93.8 | 98.6 | 5.0 | 30.8 | 59.7 | 72.5 |
| 72B | 18 | 900 | .84 | 51.7 | 80.2 | 94.2 | 98.6 | 5.2 | 31.1 | 60.8 | 73.5 |
| 20 | 18 | 900 | .84 | 44.9 | 74.4 | 92.0 | 97.9 | .0 | 18.6 | 52.5 | 72.6 |

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Plasticity of Coals Tested

The plastic properties of all coals and blends studied in the survey of carbonizing properties of American coals during the year were determined by the Agde-Damm dilatometer and by the Davis and Gieseler plastometer test methods.[67] Tests on a number of other coals and blends were also made by one or more of these methods.

Low-rank, high-volatile A coal 71 (table 4), containing 9.1 percent oxygen, showed a plastic temperature range of 137° C. by the Davis plastometer method and a maximum fluidity of 1,020 dial divisions per minute by the Gieseler plastometer method. These values are higher than are usually observed for coals of such low rank. In tests by all three methods a large amount of gas was evolved by this coal, which caused termination of the Gieseler test at a low temperature of around 430° C. and a high free-swelling index of 2.0 in the Agde-Damm dilatometer test. Blends 71A, 71B, 71C, and 71D showed characteristic plastic properties for blends of high-volatile A rank. Coal 72 is a typical high-volatile A coal and has plastic properties characteristic of a coal of this rank. Its blends also were typical. Coal 73 is a low-rank, high-volatile A coal containing 10.9 percent oxygen. This coal and its blends did not fuse in the Davis plastometer test, showed a low fluidity in the Gieseler plastometer test, and contracted continuously up to 500° C. in the Agde-Damm dilatometer test. Coal 74 is a high-rank, low-volatile coal and, except for its higher characteristic temperatures, showed much the same plastic properties as did low-rank, high-volatile A coal 73. These two coals are near the two extremes of rank defining coking coals. Similar data on the plastic properties of a number of other coals corresponding in rank to coals 74 and 73 have been observed previously.

Data were obtained during the year on the plastic properties of Lower Sunnyside- and Upper Sunnyside-bed coals of Utah. These coals lie near the borderline dividing high-volatile A from high-volatile B bituminous coals, and they are extremely sensitive to oxidation. They have poor fusion characteristics as compared with high-rank, high-volatile A coals. In general, the Lower Sunnyside coals are more fluid than those of the Upper Sunnyside bed. Comparative tests of the adsorption of toluene vapor by minus-1/4-inch coke breeze produced from Pittsburgh and Lower Sunnyside coals showed that the Pittsburgh breeze adsorbs more toluene than does the Lower Sunnyside breeze. This observation suggests that Pittsburgh breeze should be better to add to a coal to improve the quality of semicoke. Tests in a commercial, low-temperature carbonization plant have shown this to be true.

Numerous data obtained by the Bureau of Mines and other laboratories have established that the low fluidity observed in the low-volatile group of

67/ Brewer, R. E., Plastic and Swelling Properties of Bituminous Coking Coals: Bureau of Mines Bull. 445, 1942, 260 pp.



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bituminous coals increases in the medium-volatile group, attains its maximum in the high-volatile A group, and then decreases again. The highest fluidity is reached in the high-volatile A coals containing 63 to 66 percent of dry, mineral-matter-free fixed carbon. The fluidity decreases rapidly with coals containing 60 percent or less dry, mineral-matter-free fixed carbon, especially in coals of high oxygen content. Irregularities in this general relationship between plasticity or fluidity data and the corresponding A.S.T.M. classifications of bituminous coals by rank may usually be explained if the petrographic composition of the exceptional coals is considered. For example, although Lower Banner-, Sewell-, and Bakerstown-bed coals are of almost identical rank, the Lower Banner-bed coal shows a much higher fluidity by the Gieseler plastometer test than do the Sewell- and Bakerstown-bed coals. Lower Banner coal contains 36 percent of bright, 53 percent of semisplint, and 11 percent of cannel coal. In contrast, the other two are predominantly bright coals and contain no cannel coal.

The plastic properties of samples of a number of different coals that had been oxidized progressively in air at 99.3° C. have been determined. Plasticity and fluidity were reduced by progressive oxidation. The relationship between Gieseler maximum fluidity and time of oxidation may be expressed by the equation,

$$F = b + t^m,$$

where F = Gieseler maximum fluidity in divisions per minute;

t = time of oxidation, in days in air at 99.3° C.;

b and m = constants whose values depend on the rank of the coal.

Logarithms of the values of F as ordinates plotted against logarithms of the values of t as abscissas for experimental data obtained on two low-volatile coals, two medium-volatile coals, and three high-volatile A coals gave families of straight lines for each of the three groups. The slopes of the lines representing the high-volatile A coals are steeper than those for the medium-volatile coals, which, in turn, are steeper than those for the low-volatile coals. The relative order of lines plotted on a chart for coals of the three groups and for individual coals of each group accord with the characteristic rates of oxidation of the seven coals.

Some cooperative tests with the Koppers Co., Seaboard Division, Kearny, N. J., have been made on the same coals, using two Gieselper plastometers.



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Differences in constructional features of the two instruments and test procedures in the two laboratories have been largely eliminated with the view of standardizing the apparatus and test procedure.

## Effect of Conditioning Coal on Its Coking Properties

### Survey of Storing Qualities of Coking Coals and Changes Caused by Storage and Oxidation

Operators of commercial coke ovens must store large quantities of coal to assure continuity of operation and supply of usable coke for blast furnaces. To assist them in selecting coals that store well and to aid in the development of methods for preventing deterioration in storage, an accelerated weathering test was developed.

Samples of 1/4-inch slack, representative of coal from many different beds, have been oxidized progressively and carbonized at 800° C. in steel retorts holding 90 pounds of coal. Thus the samples of coke obtained are large enough for standard tests of strength and quality. The length of time each coal can withstand the action of air at 100° C. before losing its coking power is defined as its "durability of coking power," a specific property of coal.[66/]

Table 11 lists the sources, partial analyses, and durability of coking power of 15 coals. The last column shows the relative durability of coking power based upon Pittsburgh coal as unity. Comparing coals 68 and 71, the extreme cases, it can be said that if the two coals are stored under conditions that are exactly equal as to temperature, particle size, etc., coal 71 would be expected to store 16 times as long as coal 68 and still yield commercial-grade coke.

The data in this table show that the high-volatile coals in general have the greatest durability of coking power but that if the high-volatile coals also have high oxygen content, the durability of coking power may be low. The following equation served to predict with fair accuracy the durability of coking power of 13 of the 15 coals tested:

$$\text{Durability} = 1.22\,(V)_o - (O)_o\,1.65 - 11.28$$

where $(V)_o$ = volatile matter content of fresh coal, percent, moisture- and mineral-matter-free basis,

$(O)_o$ = oxygen content of fresh coal, percent, moisture- and ash-free basis.

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66/ Schmidt, L. D., Elder, J. L., and Davis, J. D., Influence of Storage on Caking and Coking Properties of Coal: Ind. Eng. Chem., vol. 36, 1943, pp. 150-155.



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TABLE 11. - Sources, rank, volatile-matter content, oxygen content, and durability of coking power of coals tested

| Coal No. | Bed | County and State | Rank[1] | Volatile-matter content[2] $(V)_o$ | Oxygen content[3] $(O)_o$ | Durability of coking power | |
|---|---|---|---|---|---|---|---|
| | | | | | | Days | Ratio to Pittsburgh-bed coal; |
| 57 | Pocahontas No. 4 | Raleigh, W. Va. | Low-volatile | 17.3 | 2.5 | 3.4 | 0.25 |
| 56 | Pocahontas No. 3 | Wyoming, W. Va. | Do. | 18.3 | 2.4 | 6.5 | .48 |
| 55 | Sewell | Do. | Medium-volatile | 22.5 | 2.8 | 10.4 | .77 |
| 64 | Bakerstown | Tucker, W. Va. | Do. | 23.1 | 3.2 | 9.7 | .72 |
| 58 | Lower Banner | Buchanan, Va. | Do. | 23.1 | 2.9 | 11.1 | .82 |
| 60 | Lower Freeport | Indiana, Pa. | Do. | 26.4 | 3.9 | 15 | 1.1 |
| 59 | Upper Freeport | Monongalia, W. Va. | High-volatile A | 32.0 | 5.7 | 12.6 | .93 |
| 53 | Pond Creek | Pike, Ky. | Do. | 34.3 | 6.1 | 10.9 | .81 |
| 67 | Taggart | Harlan, Ky. | Do. | 37.3 | 6.5 | 13.5 | 1 |
| 72 | Thick Freeport | Allegheny, Pa. | Do. | 38.3 | 6.3 | 12.6 | .93 |
| 73 | McAlester | Pittsburg, Okla. | Do. | 39.2 | 8.6 | 2.4 | .18 |
| 52 | Pittsburgh | Allegheny, Pa. | Do. | 39.3 | 7.1 | 13.5 | 1 |
| 54 | High Splint | Harlan, Ky. | Do. | 39.6 | 8.8 | 2.4 | .18 |
| 71 | Bevier | Cherokee, Kans. | Do. | 42.8 | 6.5 | 20.8 | 1.54 |
| 68 | Henryetta | Okmulgee, Okla. | High-volatile B | 38.0 | 7.2 | 1.3 | .10 |

1/ All of these are bituminous coals, and the samples are representative of the bed at the points taken.
2/ Fresh coal, moisture- and mineral-matter-free basis.
3/ Fresh coal, moisture- and ash-free basis.



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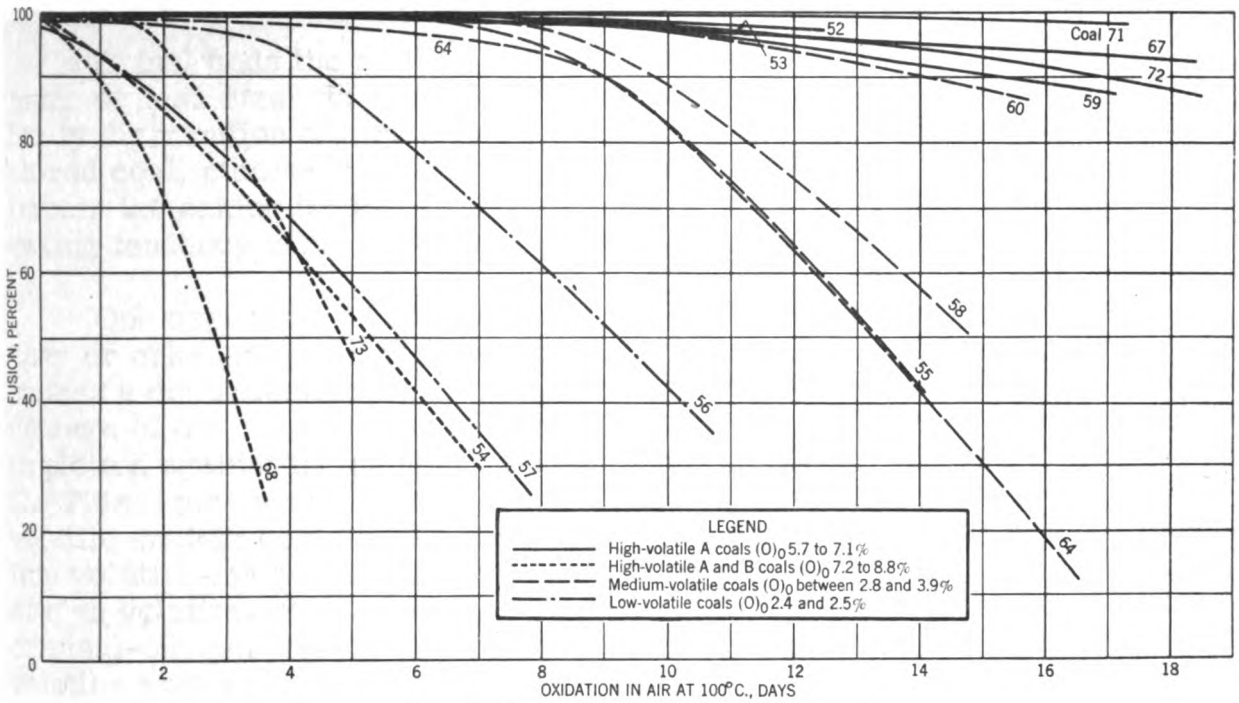


Figure 10.—Effect of storage (accelerated) of coal on fusion.

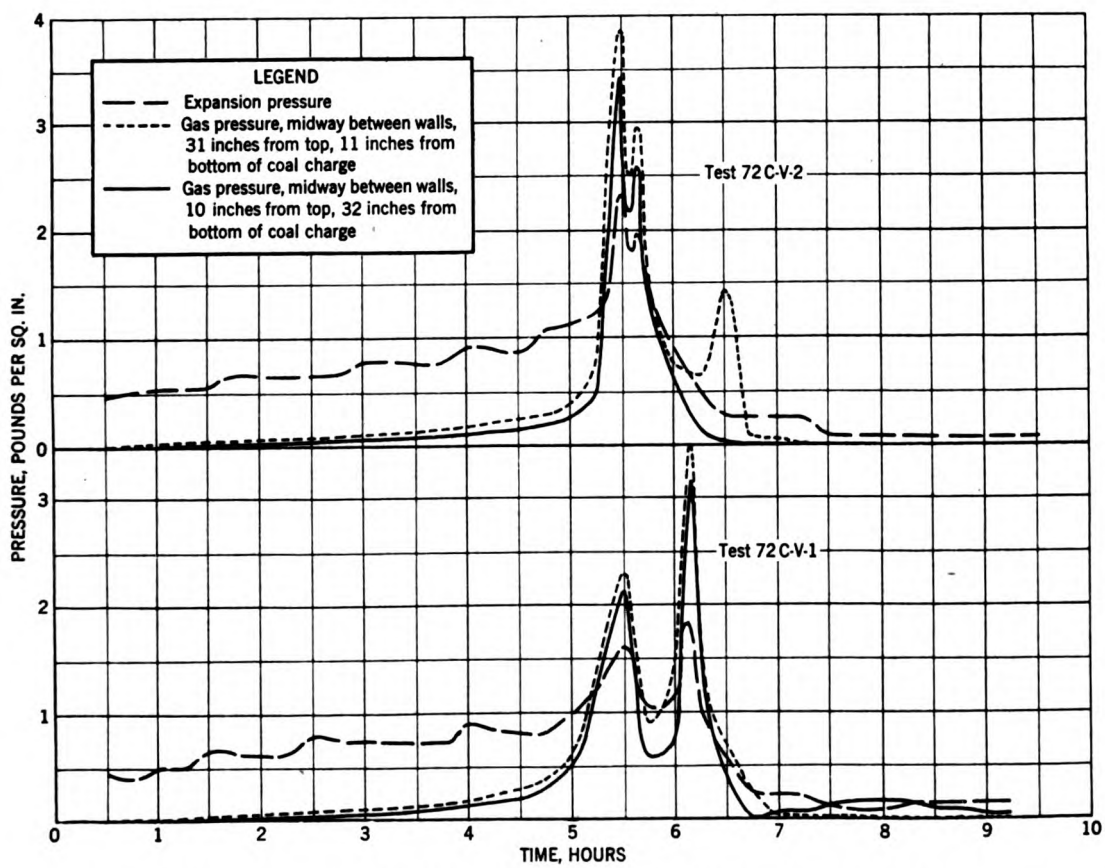
LEGEND
Expansion pressure
Gas pressure, midway between walls, 31 inches from top, 11 inches from bottom of coal charge
Gas pressure, midway between walls, 10 inches from top, 32 inches from bottom of coal charge
Test 72C-V-2
Test 72C-V-1
PRESSURE, POUNDS PER SQ. IN.
TIME, HOURS

Figure 11.—Pressures developed in vertical-slot oven by blend of 80 percent Thick Freeport coal and 20 percent Pocahontas No. 3 coal.

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Effect of Storage on Caking in Fuel Beds

In fuel beds the melting and coalescence of coal into agglomerates of more or less strength often occasion difficulties of combustion, such as faulty distribution of air. For this reason it may often prove advisable to burn stored coal, outcrop coal, or coal that has been deliberately preoxidized to impair the caking tendency. The amount of oxidation required to lessen the caking tendency varies greatly for different coals.

One aspect of the caking tendency is measured by the amount of unfused char or coke breeze in the coke after carbonization. Progressive oxidation causes a continued increase in the quantity of loose char. In figure 10 the percentage of the coke charge that remains on a 1-inch screen (percent fusion) is plotted against the number of days oxidation of 1/4-inch slack in air at 100° C. This figure shows that, in general, the caking tendency of coals of low volatile-matter content was destroyed more quickly than that of those of medium volatile-matter content and these in turn were less resistant than coals of high volatile-matter content. However, the caking tendency of coals of high original-oxygen content is destroyed quickly, regardless of the content of volatile matter.

Comparisons made at the point where each coal had been oxidized just enough to decrease the strength of coke made in large retorts by 15 percent showed that, on the average, the fusion had decreased 12 percent. If fusion is taken as a measure of caking tendency, these results indicate that in storage the caking tendency decreases at about the same rate as coking power, as measured by strength of coke.

At the same point (15-percent reduction in strength of coke), the agglutinating value of the coals had decreased on an average of 38 percent. This relatively rapid decrease in agglutinating value with oxidation adds to the value of the agglutinating test for measuring the extent of oxidation of stored coal.

Agglomerating indexes obtained by examining buttons from the standard volatile-matter determination on 55 coals at various stages of oxidation showed that the coals classified as good-caking had an average fusion (in a large retort) of 93.4 percent. The coals classified as fair- and poor-caking had, on an average, 83.8 and 51 percent fusion, respectively. Thus, the agglomerating-index test is of value as a measure of caking tendency.

When each coal had been oxidized enough to cause a 15-percent decrease in strength of coke, the average decrease of heating value was only 1.8 percent. This apparent decrease in heating value would be smaller if allowance were made for the gain in weight of coal resulting from addition of oxygen. Hence, it is apparent that the caking tendency can be destroyed by oxidation long before the loss in heating value becomes commercially important.



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## Determination of Swelling Properties of Coal During the Coking Process

Studies of the expanding properties of coal were continued in the two types of test ovens.[69] In the vertical-slot oven, in which the coal is heated from two sides and the pressures developed under constant volume are measured, blends actually being used or proposed for use in commercial ovens were tested. Data were obtained on pressures exerted on the oven walls, their relation to gas pressures within the coal, and the physical properties of the cokes formed. The sole-heated oven, in which the expansion or contraction of a coal under constant pressure or the pressure developed at constant volume is measured, was used to continue standard tests on coals received in the survey of gas-, coke-, and byproduct-making properties of American coals. It was used also to investigate the effect of other factors on expanding properties.

Figure 11 shows a test in progress in the vertical-slot oven. A recent addition to the apparatus is a device, shown in the lower foreground, for automatic adjustment of the applied pressure necessary to balance the pressure developed in the coal. A contact on the movable wall carriage moving between two fixed contacts operates a motor which, through reducing gears, turns a screw to apply or release pressure to maintain the coal charge at constant thickness. Tests in this oven are automatic and require only general observation.

Typical pressure data obtained in duplicate tests in the vertical-slot oven are shown in figure 12. The coal blend tested contained 80 percent high-volatile coal from the Thick Freeport bed (coal 72) and 20 percent low-volatile coal from the Pocahontas No. 3 bed (coal 56). The expansion pressures exerted on the oven walls and the gas pressures at two points in the coal midway between the walls are plotted against time. The peaks of pressure obtained at or near the time of meeting of the two plastic layers are characteristic of dangerously expanding or "borderline" blends. The pressure on the walls follows closely the trend of the gas pressures at the center of the charge when the plastic layers approach or reach this point and is of the same order of magnitude. This evidence supports the theory that pressure on the wall is caused by confinement of the gaseous products of decomposition within the plastic coal. The fluctuations in the peak pressures probably are caused by alternate confinement and release of the evolved gases. The first rapid rise of pressure occurs at the same time in the duplicate tests, but another peak is reached later in only one of the tests. It is believed that the building up and release of pressure in the double plastic layer are affected by many slight variations of conditions, so that duplication of time of occurrence and magnitude of peaks of pressure cannot be confined within narrow limits. In other words,

69/ McCartney, James T., and Davis, Joseph D., Expansion of Coal During Coking: Bureau of Mines Rept. of Investigations 3644, 1942, 23 pp.



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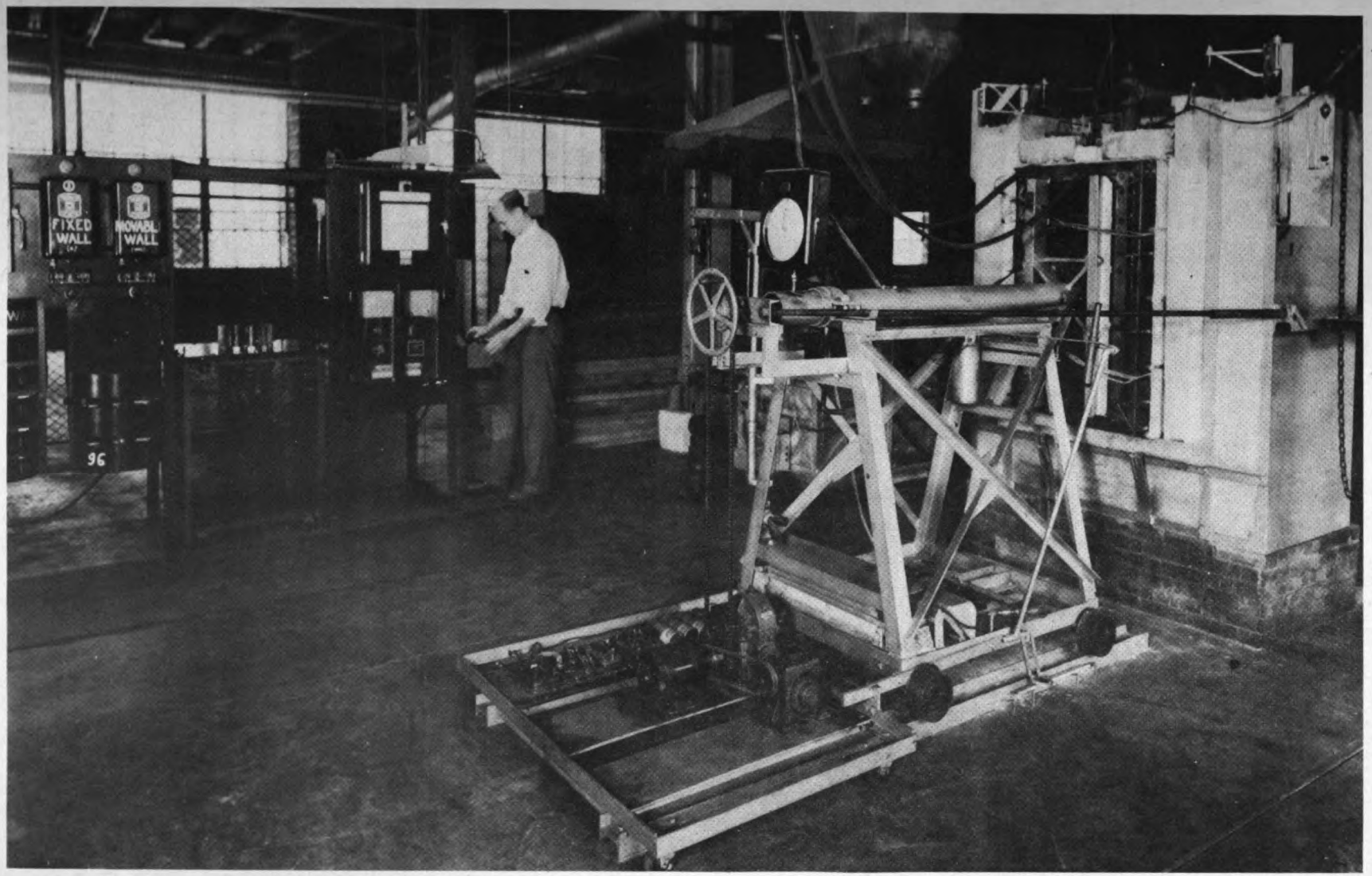


Figure 12.—Vertical-slot oven.

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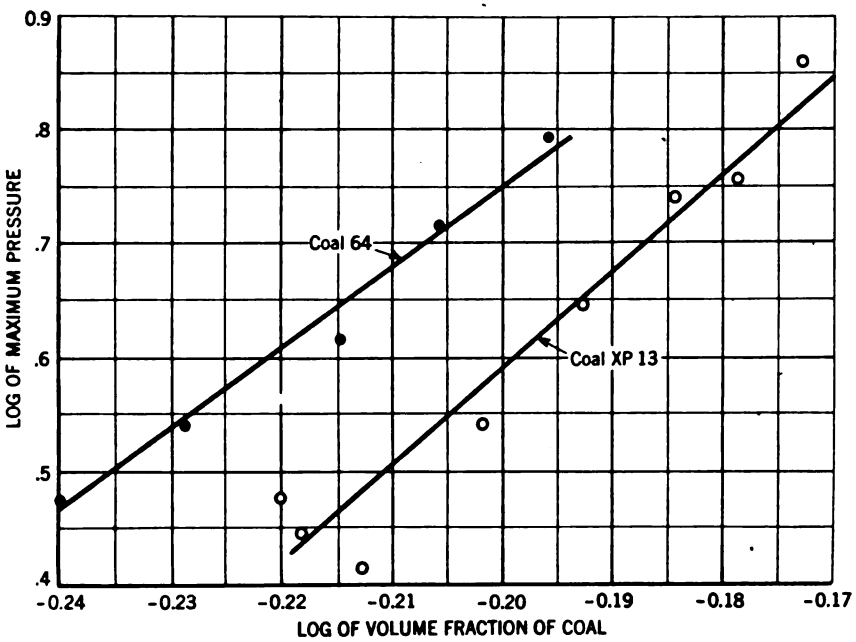


Figure 13.—Relation of maximum pressure to volume fraction of coal in charge.

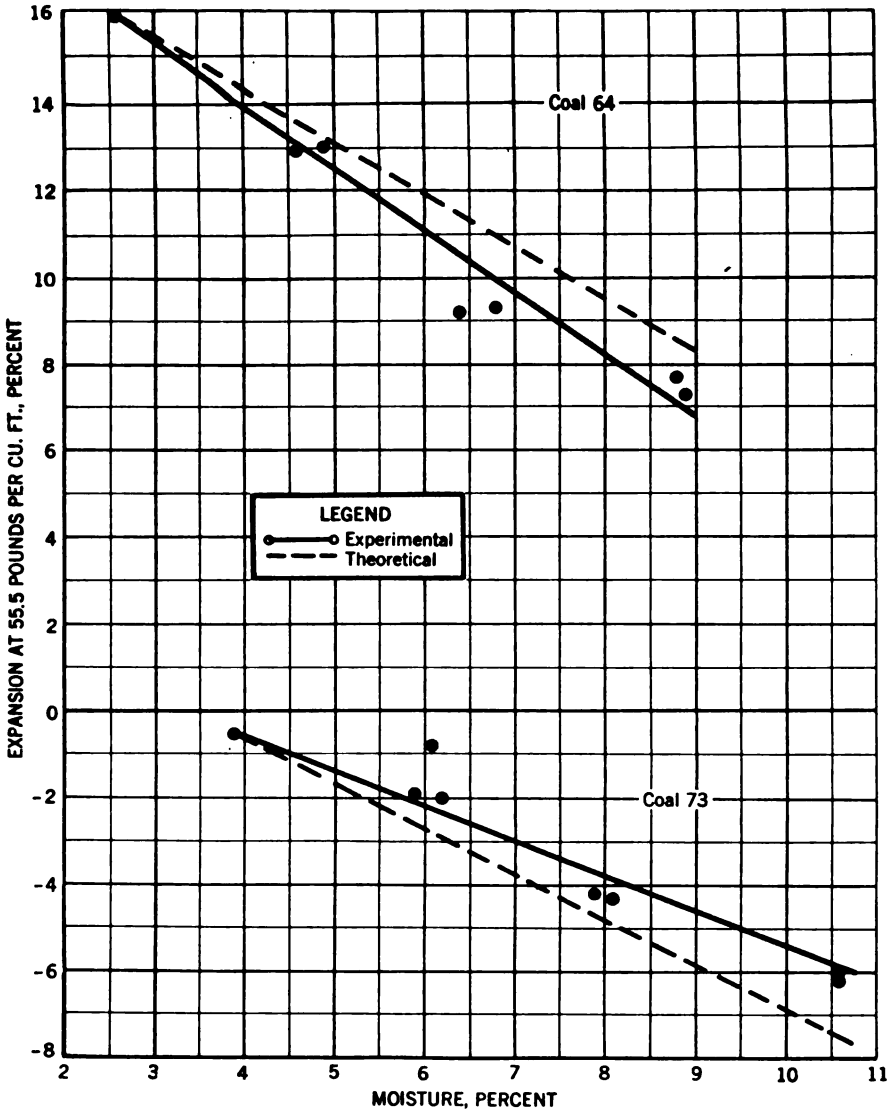


Figure 14.—Relation between moisture content and expansion.

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the maximum pressure that a certain blend might exert on the walls of ovens varies in different ovens and in different charges in the same battery. These variations probably are a function of the peculiar plastic properties of different coals and blends, so that some will vary less than others in duplicate charges. The vertical-slot-oven tests show the order of magnitude of the pressures to be expected with a given coal and can be used with a reasonable factor of safety to predict its "degree of dangerousness."

Effect of Packing of Charge

One of the important variables affecting pressure development in a coking coal charge is its bulk density. It has been shown previously that the total expansion or contraction of a charge at constant pressure is directly proportional to the bulk density. Series of tests have been made on two coals in the sole-heated oven in which the maximum pressure developed under constant volume at different bulk density was measured. Coal XP13 was a medium-volatile coal from the Sewall bed and coal 64 a medium-volatile coal from the Bakerstown bed. The results are summarized in figure 13. Instead of plotting bulk density in the figure, another term is used that describes the degree of packing of the charge more accurately. As coals vary in specific gravity, two different coals charged at the same bulk density would not have the same condition of packing. Therefore, the fractional part of the volume of the charge occupied by coal is used instead of bulk density. This quantity is proportional to the bulk density for a given coal and equals bulk density divided by solid coal density, both expressed pounds per cubic foot. The maximum pressure was found to be not directly proportional to the bulk density, so the plotting was done on a log-log basis. The points for both coals lie fairly close to straight lines whose equations are: For coal XP-13, $P = 195.2\ C^{8.5}$, where P is the maximum pressure developed in pounds per square inch and C is the volume fraction of the coal in the charge $C = \frac{\text{bulk density}}{\text{solid-coal density}}$ and for coal 64, $P = 140.3C'$. It is evident that the relation between maximum pressure and bulk density is not a simple one, and the prospect of establishing a theoretical basis for calculating pressures from one bulk density to another that would apply to all coals is not promising. Some of the factors that affect the relationship are these: (1) With increased bulk density, there is, in a given space, more coal that releases gas to produce pressure; (2) there is less void space to provide relief for this pressure; (3) as the developed pressures increase at higher bulk density, there is a greater tendency for the uncoked portions of the charge to compress, which leads to cumulatively higher pressures as coking proceeds. The effect of various factors on expanding properties, as determined in the sole-heated oven with heating from one side only, may not apply in exactly the same way to conditions of two-sided heating, but the general effect should be similar.



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Effect of Moisture

Tests were made on two coals in the sole-heated oven to study the effect of moisture on expansion or contraction under constant pressure. The results are shown in figure 14. In the series of tests with coal 64, the thickness of the charge and dry bulk density were kept constant, so that the actual bulk density increased with moisture content. The effect was to increase the water content and thus the weight of the coal contained in a given volume. In a series on coal 73 - a high-volatile coal from the McAlester bed, Oklahoma - the weight of charge and the actual bulk density were kept approximately constant, so that the effect was that of replacing coal by water. The second set of conditions approached practical operations more closely. The theoretical curves are drawn on the assumption that a given amount of dry coal would have the same expansion, regardless of the amount of water mixed with it. The bulk density would, of course, change so that, if the results are calculated to a fixed bulk density, the expansion decreases regularly with moisture content. The observed results agree fairly well with the calculated figures. They lie approximately on straight lines whose slopes deviate slightly from those of the theoretical curves and in opposite directions for the two coals. It was thought that increased moisture content would cause a decrease in the heating or coking rates, resulting in a deviation from the theoretical expansion, but no regular or appreciable change in coking rates was observed. It may be concluded that, although moisture affects the bulk density, of itself it has little effect on expansion.

Effect of Inert Material

The effect of inert material on expansion in the sole-heated oven at constant pressure was studied for coal 64, previously described, and coal 56 from the Pocahontas No. 3 bed. Figure 15 shows the data obtained. The theoretical values of expansion are found from the assumption that the added inert material replaces some of the coal so that the expansion of the charge is reduced. The agreement between the observed and calculated values is fair. For both coals, the experimental values are always lower, although the relationship is still straight line. Again there was no evidence that the deviations could be attributed to changes in rates of heating. A possible explanation is that the admixed sand decreases the fusing ability of the mixture, giving values of expansion lower than those calculated on a basis of simple substitution of sand for coal.

Effect of Blending Coal

The effect of blending on expanding properties was investigated in two series of tests in the sole-heated oven at constant pressure. Medium-volatile coals - 60 from the Lower Freeport bed and 64 from the Bakerstown bed were



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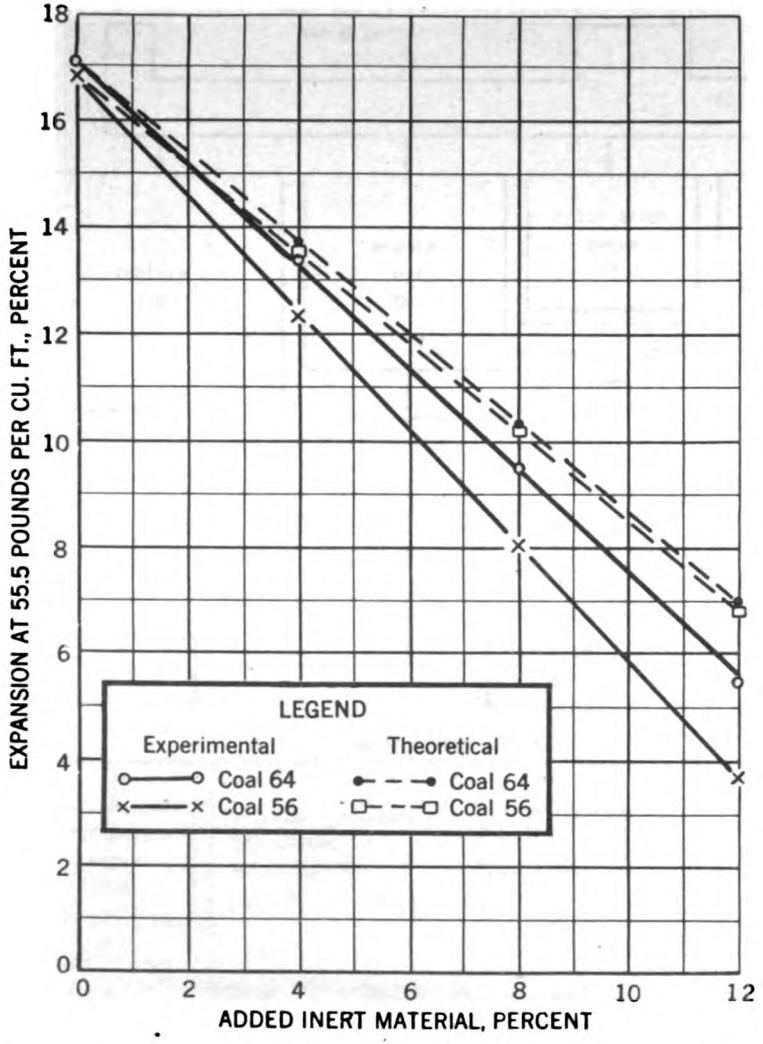


Figure 15.—Effect of inert material on expansion of coal.

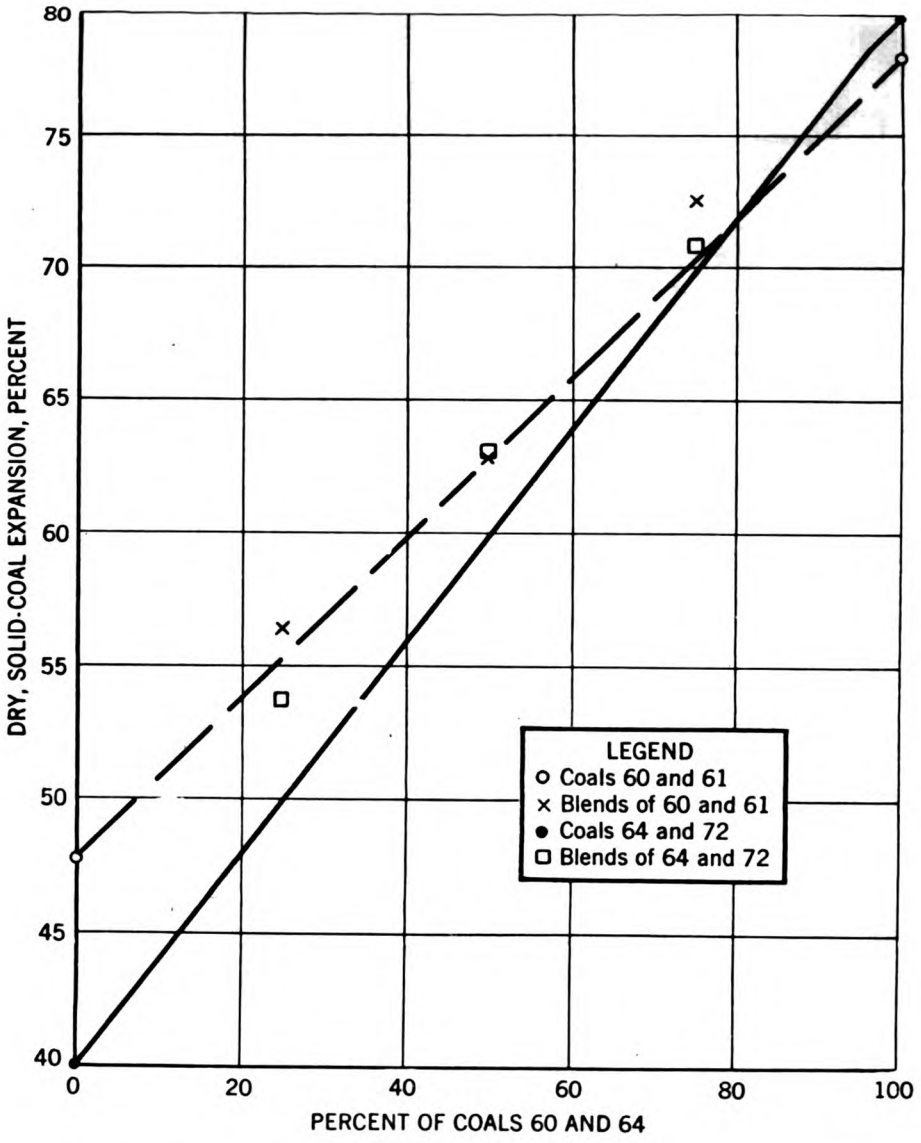


Figure 16.—Expansion of blends and their constituent coals.

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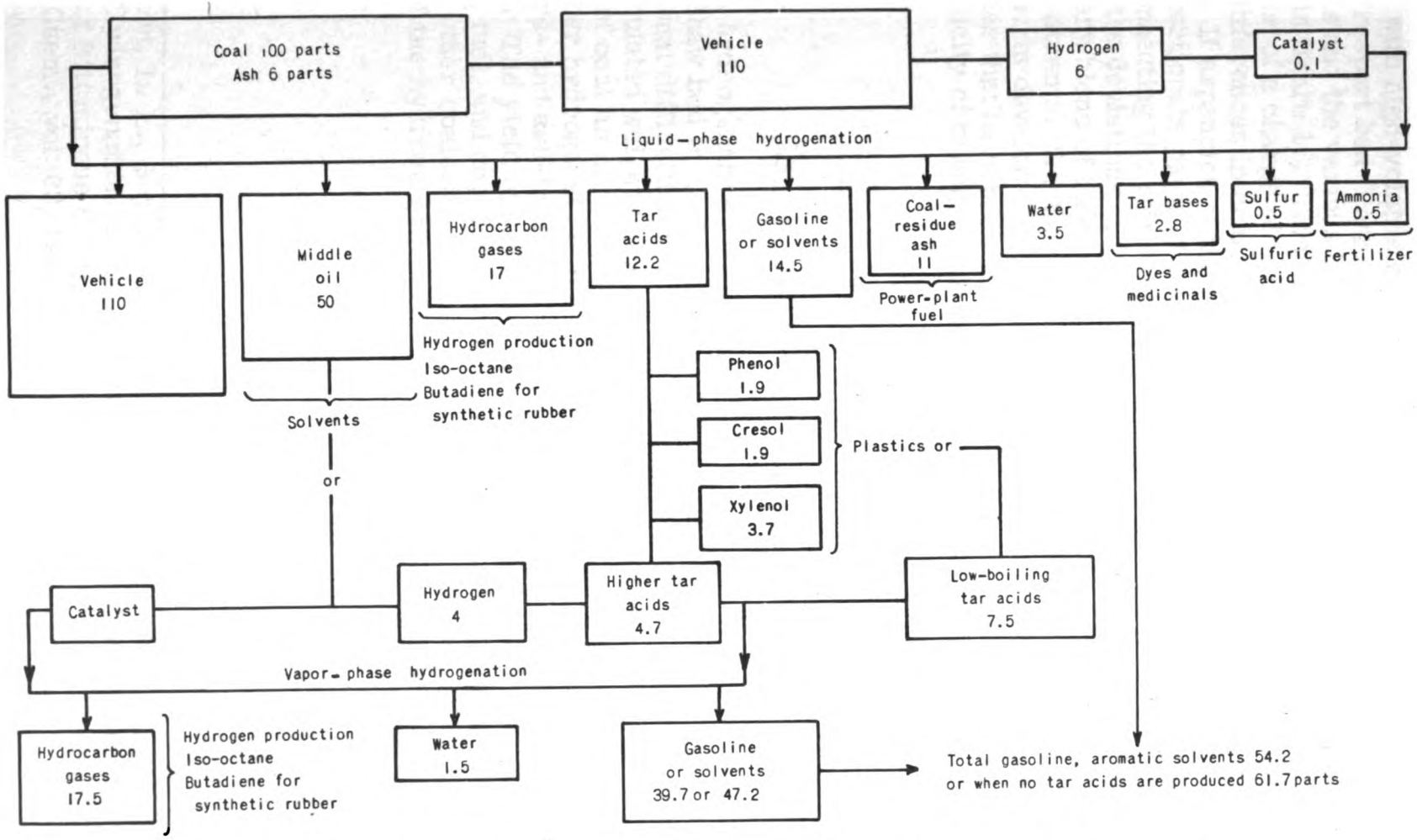


**Figure 17.—Approximate yield of products from hydrogenation of Pittsburgh-bed bituminous coals.**

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blended with high-volatile coals 61 from No. 1 bed (Kentucky) and 72 from the Thick Freeport bed (Pennsylvania), respectively. The expansion of each of the coals and the various blends was calculated to the dry, solid-coal basis and plotted in figure 16. This method of calculation, which shows the theoretical expansion of a charge of moisture-free solid coal without void spaces, eliminates differences in coals caused by varying moisture content and specific gravity. If expansion of the blends were directly proportional to expansion of the proportionate parts of the constituents, the points would lie on the straight lines connecting the points for the separate coals. For these two series of blends, the deviations are not large, and it appears that the approximate expansion of any blend of these coals could be calculated, knowing the results for the constituents. Whether this would be true of blends of other coals or apply to pressures developed under constant volume is uncertain. Studies of plastic properties that have been shown to correlate well with expansion indicate that the plasticity of blends is not, in general, proportional to those of the separate coals.

## HYDROGENATION AND LIQUEFACTION

### Hydrogenation Assay of Coal from Alaska

A hydrogenation assay was made on a sample of bituminous coal from the Upper Shaw bed in the Eska mine, Alaska. This coal hydrogenated readily; no exceptional difficulties were noted. The yield of assay oil was 73 percent of the calculated weight of moisture- and ash-free coal or 62 percent of the weight of coal as mined and washed. This assay oil was converted to gasoline by further hydrogenation; the yield of gasoline was 51 percent of the weight of moisture- and ash-free coal and 43 percent of the weight of coal as mined and washed. The yield of gasoline based on the total coal used for all purposes (power, fuel, and coal for hydrogenation) is given in table 12, with comparable data on other coals.[70] A diagram showing the character and amount of products of the hydrogenation of a typical bituminous coal is given in figure 17.

70/ Hirst, L. L., Boyer, R. L., Eisner, A., Pinkel, I. I., and Storch, H. H., Hydrogenation of High-Volatile Bituminous Coals; Summary of Assays of Bituminous Coals, Sub-bituminous Coals, and Lignites: Ind. Eng. Chem., vol. 33, 1941, pp. 1068-1072.

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TABLE 12. - Yield of crude oil and estimated gasoline yield based on total coal (as mined, or as mined and washed) used for all purposes

Basis of Calculation: 4 tons of Pittsburgh-bed coal or its equivalent in moisture- and ash-free coal per ton of gasoline, and 70 percent by weight conversion of crude oil (sp. gr., 0.89) to gasoline (sp. gr., 0.75).

| Coal bed and State | Weight percent | | Gallons per ton | |
|---|---|---|---|---|
| | Crude oil | Gasoline | Crude oil | Gasoline |
| Mary Lee, Ala. | 20.3 | 14.2 | 54.5 | 45.5 |
| Upper Freeport, W. Va. | 24.1 | 16.9 | 65.0 | 54.1 |
| Pittsburgh, Pa. | 25.0 | 17.5 | 67.5 | 56.0 |
| Black Creek, Ala. (washed) | 25.7 | 18.0 | 69.5 | 57.6 |
| Upper Shaw, Alaska (washed) | 24.1 | 16.9 | 65.0 | 54.1 |
| Lower Sunnyside, Utah | 26.0 | 18.2 | 70.0 | 58.2 |
| No. 4, Ind. | 21.5 | 15.1 | 58.0 | 48.3 |
| No. 6, Ill. | 23.4 | 16.4 | 63.0 | 52.5 |
| McKay, Wash. | 23.0 | 16.1 | 62.0 | 51.5 |
| Puritan, Colo. | 17.5 | 12.3 | 47.0 | 39.4 |
| Rosebud, Mont. | 15.6 | 10.9 | 43.0 | 34.9 |
| Monarch, Wyo. | 19.1 | 13.4 | 51.5 | 42.9 |
| Beulah, N. Dak. | 12.1 | 8.5 | 32.5 | 27.2 |
| Velva, N. Dak. | 12.5 | 8.8 | 33.7 | 28.2 |

## Characterization of Assay Oils

The oils obtained by liquid-phase hydrogenation of eight coals ranging in rank from medium-volatile bituminous to lignite were washed to remove tar acids and bases and then distilled through a packed laboratory column of about 50 theoretical plates. From the density, refractive index, and sulfuric acid-solubility data some information is deduced concerning the probable components of the fractions. Several liters of oil from a bituminous coal and from a lignite were sulfonated, and the residual saturated fractions distilled. For such fractions these properties and the aniline point were determined. Finally the neutral oil from the hydrogenation of one bituminous coal was separated into eight fractions by the distillation of about 400 pounds in a packed column 14 feet high and 0.5 foot in diameter, which contained the equivalent of about 14 theoretical plates; subsequently the fractions thus obtained were redistilled in the 50-plate laboratory column. In this way about 100 fractions of the oil were obtained, for which density, refractive index (of fraction before and after extraction with 98 percent sulfuric acid), sulfuric acid-solubility, and carbon and hydrogen content were determined.[71/]

71/ Hirst, L. L., Eisner, A., Field, J. H., Cooper, H. M., Abernethy, R. F., and Storch, H. H.,Hydrogenation and Liquefaction of Coal. Part 3-Characterization of Assay Oils: Bureau of Mines Tech. Paper 646, 1942,,27. pp.



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Interpretation of the results is complicated by the presence of appreciable quantities of oxygenated compounds and by a large number of constant boiling mixtures. Between 50 and 90 percent of all of the fractions boiling below 200° C. and 20 to 50 percent of those boiling about 200° C. are insoluble in 98-percent sulfuric acid; and aniline points show that the residual oils or saturates consist mainly of naphthenic compounds, namely, alklcyclopentanes, alkylcyclohexanes, and alkylbicyclodecanes (saturated alkylhydronaphthalenes). In the 50° to 85° C. fractions the presence of large portions of branched hexanes, cyclopentane, methylcyclopentane, and cyclohexane is apparent. For the fractions boiling below about 150° C. the material insoluble in 86 percent sulfuric acid, but soluble in 98 percent acid (that is, the "aromatics" fraction) contains large amounts of branched-chain paraffine and naphthenes, as well as benzene, toluene, and xylenes. For the fractions boiling above 150° C. the "aromatics" fraction contains only small amounts of paraffinic or naphthenic hydrocarbons; the main components are benzene and naphthalene homologs. The material soluble in 86 percent sulfuric acid (that is, the "olefins" fraction) is about 10 percent of the total oil and contains reactive olefins that forms peroxides upon distillation. These probably are cyclic olefins. Oxygenated compounds are present in all of the fractions in amounts ranging from traces to as much as about 20 percent. No information is yet available concerning their constitution.

## Refining of Coal-Hydrogenation Gasoline

As shown in the preceding section, the gasoline fractions of the liquid-phase coal-hydrogenation oils contain appreciable amounts of materials that form peroxides upon distillation. These organic peroxides act as detonators when the gasoline is used in an internal-combustion engine and thereby lower the octane number of the gasoline. It has been found that the most effective refining procedure is to heat the gasoline mixed with 10 percent of its weight of an active clay (such as bentonite), for 3 hours at its boiling point, with high-speed stirring. Such treatment resulted in the octane number 68-69 and in the number 80-81 when 3 cc. of tetraethyl lead was added to each gallon of gasoline. Further refining studies are in progress on gasolines from both the liquid- and vapor-phase stages of coal hydrogenation.

## Effect of Petrographic Composition and Rank of Coal

Comparison of the amounts of residue calculated from the petrographic composition with the residues actually obtained in continuous hydrogenation shows that petrography is a useful tool for predicting the residue inert to hydrogenation. The conclusions from tests in small bombs on the relation between petrographic composition and residue are confirmed in continuous hydrogenation. A series of tests in small bombs (or rotating autoclaves) of 1-liter capacity, covering a wide range of rank, including peat, brown coal, lignite, subbituminous coal, and bituminous coal, indicate that hydrogenation under



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optimum conditions results in liquefaction of large proportions of all these materials.72/ A sample of anthraxylon from anthracite containing 94.9 percent carbon was liquefield only slightly upon hydrogenation. Data are not available yet to indicate whether the transition from low-volatile bituminous coal to anthracite is accompanied by a gradual or a relatively sharp change in liquefaction. Low-rank coals appeared to be more sensitive than bituminous coal to change of experimental conditions. In general, higher pressures and lower temperatures proved to be desirable in experiments with subbituminous and lignitic coals. For coals that contain less than 82 percent carbon the yield of carbon dioxide increases rapidly with decreasing rank of the coal. This increased elimination of oxygen as carbon dioxide explains the fact that low-rank coals do not use much more hydrogen than high-volatile bituminous coals.

In splint coals that contain appreciable quantities of opaque matter 40 to 80 percent of the opaque attritus can be liquefied, the proportion corresponding roughly to the opacity. The tests on hand-picked fusain show that 10 to 55 percent fusain can be liquefied. Spores, resins, and oil algae that occur in quantity in cannel coals are liquefied readily under mild conditions of hydrogenation and the products obtained from these constituents contain more saturated hydrocarbons than those obtained from bright coal.

## Chemistry of Coal Hydrogenation

Additional data were obtained from experiments on rates of hydrogen absorption, oxygen removal, and coal liquefaction in a 1,200-cc. bomb using 50 to 100 grams of powdered Pittsburgh-bed coal mixed with various amounts of tetrahydronaphthalene with and without catalysts, and for various temperatures. Analysis of these data resulted in the following outline of the nature of the physical and chemical processes involved in coal hydrogenation:

At temperatures below about 300° , the slowest or rate-determining step in the hydrogen-absorption process is the rate of reaction of hydrogen with the unsaturated groups in the original coal structure and unsaturated groups resulting from dehydration. This reaction is accelerated by catalysts, such as tin compounds. Above 300°, the rate of this chemical reaction surpasses that of the diffusion of hydrogen through a liquid film on the surfaces of the coal and catalyst; hence such diffusion is the slowest step between 300° and 370°.

Above 370°, rapid depolymerization and solvation of the coal occur. This depolymerization reaction is essentially a primary decomposition of the coal and is characterized by the large temperature coefficient observed in the first hour of reaction in the 370°-385° interval. The reaction, with hydrogen carriers or with each other, of the unsaturated fragments from the decomposition

72/ See copy p. 102.



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is more rapid than the primary decomposition of the coal; hence the latter is the rate-determining step. The primary decomposition is a thermal, non-catalytic process. The fragments from this thermal explosion react with hydroaromatic compounds, such as tetrahydronaphthalene, thereby stabilizing themselves by means of hydrogen atoms removed from the hyroaromatic. The chief function of the catalyst is rapid regeneration of the hydroaromatic compounds that serve as hydrogen carriers. The rates of oxygen elimination and of coal liquefaction are virtually independent of catalysts, when an excess of tetrahydronaphthalene is present, whereas the rate of hydrogen consumption depends markedly on the nature and amount of catalyst present.

Primary decomposition of the coal at temperatures above 385° C. is followed by secondary decomposition of the depolymerized coal. The secondary process is a noncatalytic reaction between the oxygen groups of the primary decomposition products and a reactive hydroaromatic. Concomitant with this oxygen-removal reaction there is a dehydrogenation of the coal-hydrogenation products due to thermal instability, so that the net hydrogen consumption tends to decrease with increasing temperature above 400° C. At sufficiently high temperatures this dehydrogenation results in formation of coke.73/, 74/

## INFLAMMABILITY OF COAL, METAL, AND ORGANIC DUSTS

The inflammability of 70 dust samples submitted by industry was determined during the year. These included coal-mine dusts, metal powders, synthetic resins, wood pulp, shellac, cottonseed-hull bran, and dusts from power plants, steel mills, and metallizing operations. In addition, the inflammability of numerous powders suggested as extinguishers for incendiary bombs was tested.

Metallic powders are being produced in large quantities for metallurgical and other uses. Most of these powders are inflammable and are capable of propagating an explosion when a cloud of sufficient density is formed in air and ignited. Apparatus in use for a number of years in studies of the inflammability of coal-mine dusts was modified and improved to handle the metal dusts. The metals tested were aluminum, antimony, cadmium, chromium, copper, iron, lead, magnesium, Dowmetal (an alloy containing chiefly magnesium), tin, titanium, zinc, and zirconium. In most instances several samples of a given metal were obtained from different sources; thus there were eight samples

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73/ Storch, H. H., Hawk, C. O., and O'Neill, W. E., Kinetics of Hydrogen Consumption, Oxygen Elimination, and Liquefaction in Coal Hydrogenation. Nature of the Catalytic Reactions: Jour. Am. Chem. Soc., vol. 64, 1942, pp. 230-236.

74/ Storch, H. H., Chemistry of Coal Hydrogenation: Chem. Rev., vol. 29, 1941, pp. 483-499.



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of iron powder and five of magnesium. For comparative purposes, parallel tests were made of Pittsburgh coal dust, cornstarch, and wood pulp, the inflammability of which is well known as a result of long study. The metals tested may be divided into three broad groups A, highest explosibility; B, medium explosibility; and C, lowest explosibility.

## A. Metal Powders of Highest Explosibility

Class A includes powdered aluminum, pure iron, magnesium, Dowmetal, titanium, and zirconium. Cornstarch and wood pulp are nonmetals in the same class. Suitable clouds of dusts of these materials are ignited readily by small sources of ignition and violent explosions result. Stronger sources of ignition do not increase the violence of the explosion appreciably. The surface condition of the powder influences the results obtained. Thus, particles of aluminum powder may have a thin coat of oxide that reduces chemical acitivity.

Zirconium is a particularly dangerous metal; a cloud of the powder produced by an air jet ignited spontaneously at room temperature and exploded. The other metals of this class had ignition temperatures ranging from 350° to 700° C., depending on the metal and the size of the particles.

Reduction of the oxygen in the atmosphere in which the powders are dispersed is not a practical method of preventing explosions of dusts of these metals. For example, explosions of aluminum dust were obtained with as little as 5.7 percent oxygen when ignited by an electric spark. Magnesium explodes in pure carbon dioxide and ignites in pure nitrogen. In the former instance, the carbon dioxide is decomposed, and in the latter magnesium nitride is formed. Explosions of powdered titanium were obtained in an atmosphere containing only 3 percent oxygen. Zirconium should be handled only as a sludge or else in evacuated containers because of its high chemical reactivity. Although wood pulp and starch ( the two nonmetals in this class) are highly explosive, they differ from the metals in that 16-percent reduction of oxygen in the atmosphere prevented explosions.

## B. Metal Powders of Medium Explosibility

Class B includes antimony, cadmium, tin, zinc, and impure iron. Pittsburgh coal dust is a comparable nonmetal in the same class. These materials are sensitive to change in the strength of the source of ignition and became nonexplosive when the oxygen in the atmosphere was reduced sufficiently. The greatest reduction was required with zinc, the maximum allowable oxygen being 10 percent.



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## C. Metal Powders of Lowest Explosibility

Class C includes copper, chromium, and lead. Carbon black is a nonmetal in this class. These powders require ignition sources of higher temperature and greater heat capacity. Under the standards adopted for coal dust, these metals would generally be considered nonexplosive. However, under more extreme conditions weak explosions are possible; also in some instances there is considerable variation in the inflammability of different samples. For example, one sample of lead was considerably more inflammable than other samples of lead. Causes of these variations remain to be determined.

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